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Benzene Emissions from Benzene Storage Tanks Background Information for Proposed Standards

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Research Triangle Park, NC

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16. ABSTRACT

Standards of Performance for the control of emissions from benzene storage tanks are being proposed under the authority of Section 112 of the Clean Air Act. These standards would apply to all new and existing storage tanks having a capacity of 4 cubic meters or larger, which are to be used for the storage of pure benzene. Existing sources will have to comply with the standard within 90 days of its effective date, unless a waiver of compliance is secured from the Administrator. This document contains background information and environmental and economic impact assessments of the regulatory alternatives considered in developing the proposed standards.

17. KEY WORDS AND DOCUMENT ANALYSIS

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Benzene Emissions from Benzene Storage Tanks — Background Information for Proposed Standards

Emission Standards and Engineering Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air, Noise, and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

December 1980

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ENVIRONMENTAL PROTECTION AGENCY

Background Information and Draft Environmental Impact Statement for Benzene Storage Tanks

Prepared by:

Don R Goodwin 10/7/80

(Date)

Don R. Goodwin
Director, Emission Standards and Engineering Division
U. S. Environmental Protection Agency
Research Triangle Park, NC 27711

1. The proposed benzene emissions standards would limit emissions of benzene from existing and new benzene storage tanks. The proposed standards implement Section 112 of the Clean Air Act and are based on the Administrator's determination of June 8, 1977 (42 FR 29332) that benzene presents a significant risk to human health as a result of air emissions from one or more stationary source categories, and is therefore a hazardous air pollutant. Affected facilities are located in 23 states and territories of the Unites States, but over 40 percent of the facilities are in the State of Texas.

2. Copies of this document have been sent to the following Federal Departments: Labor, Health and Human Services, Defense, Transportation, Agriculture, Commerce, Interior, and Energy; the National Science Foundation; the Council on Environmental Quality; members of the State and Territorial Air Pollution Program Administrators; the Association of Local Air Pollution Control Officials; EPA Regional Administrators; and other interested parties.

3. The comment period for review of this document is 60 days. Ms. Susan Wyatt may be contacted regarding the date of the comment period.

4. For additional information contact:

   Ms. S. Wyatt
   Standards Development Branch (MD-13)
   U. S. Environmental Protection Agency
   Research Triangle Park, NC 27711
   telephone: (919) 541-5477.

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METRIC CONVERSION TABLE

In keeping with U.S. Environmental Protection Agency policy, metric units are used in this report. These units may be converted to common English units by using the following conversion factors:

Metric Unit	x Conversion	=	Equivalent English Unit
LENGTH			
meter (m)	39.37		in
meter (m)	3.28		ft
VOLUME			
liters (l)	0.2642		U.S. gal
cubic meters m^3	264.2		U.S. gal
cubic meters m^3	6.29		barrels (bbl)
WEIGHT			
kilogram (10^3 grams) (kg)	2.2046		lb
megagram (10^6 grams) (Mg)	1.1023		tons
gigagram (10^9 grams) (Gg)	1,102.3		tons
ENERGY			
gigajoule (GJ)	9.48×10^5		Btu
gigajoule (GJ)	2.78×10^4		KWh
joule per gram (J/g)	0.430		Btu/lb
VOLUMETRIC FLOW			
normal cubic meters per second (Nm^3/sec)	2,242		SCFM (ft^3/min)
kilopascal (kPa)	9.9×10^{-3}		atm
kilopascal (kPa)	0.145		psi
SPEED			
meters per second (m/s)	196.86		ft/min

TEMPERATURE

Temperature in degrees Celcius (°C) can be converted to temperature in degrees Farenheit (°F) by the following formula:

$$(^\circ F) = 9/5\ (^\circ C) + 32$$

1. SUMMARY

1.1 REGULATORY ALTERNATIVES

On June 8, 1977, the Administrator of the U.S. Environmental Protection Agency determined that benzene presents a significant carcinogenic risk to human health as a result of benzene emissions from one or more stationary source categories and is, therefore, a hazardous air pollutant. Based on Section 112 of the Clean Air Act as amended August 1977, the Administrator is mandated to propose a standard which ". . .provides an ample margin of safety to protect the public health from such hazardous air pollutant." Because benzene storage has been determined to be a significant source of benzene emissions, the Administrator has evaluated several regulatory alternatives for reducing benzene emissions from this source. These regulatory alternatives were developed from the control options listed in Tables 1-1 and 1-2 for existing and new benzene storage tanks, respectively.

1.2 ENVIRONMENTAL IMPACT

The control options in Tables 1-1 and 1-2 are listed in order of increasing emissions control potential. The only options having any adverse environmental impacts are those which would require that each tank be fitted to a vapor control system (Options IV and V for new and existing tanks, respectively). Tables 1-3 and 1-4 present an assessment of the environmental, energy, and economic impacts for each of the control options for existing and new sources, respectively. As shown in these two tables, the most attractive options from an environmental viewpoint are Option V for new tanks and Option VI for existing tanks. These two options would prohibit the storage of benzene in new tanks and existing tanks, respectively.

Table 1-1. CONTROL OPTIONS FOR EXISTING BENZENE STORAGE TANKS

- Option 0 - Baseline (no additional standard)
- Option I - Each fixed-roof storage tank must be retrofitted with an internal floating roof (contact or noncontact).
- Option II - Each fixed-roof storage tank must be retrofitted with an internal floating roof (contact or noncontact); each external floating-roof storage tank must be retrofitted with a secondary seal.
- Option III - Each fixed-roof, external floating-roof, and internal floating-roof storage tank must be converted to a contact internal floating-roof storage tank with a liquid-mounted primary seal.
- Option IV - Each fixed-roof, external floating-roof, and internal floating-roof storage tank must be converted to a contact internal floating-roof storage tank with a liquid-mounted primary seal and a continuous secondary seal.
- Option V - Each fixed-roof, external floating-roof, and internal floating-roof storage tank must be fitted to a vapor control system. Two vapor control systems which have been analyzed in detail include:

  A. Steam-regenerated carbon adsorption system.

  B. Thermal oxidation system.
- Option VI - Prohibit the storage of benzene in tanks.

Table 1-2. CONTROL OPTIONS FOR NEW BENZENE STORAGE TANKS

- Option 0 - Baseline (no additional standard)
- Option I - Each fixed-roof storage tank must have an internal floating roof (contact or noncontact).
- Option II - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal.
- Option III - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.
- Option IV - Each storage tank must be fitted to a vapor control system. Two vapor control systems which have been analyzed in detail include:

  A. Steam-regenerated carbon adsorption system.

  B. Thermal oxidation system.
- Option V - Prohibit the storage of benzene in tanks.

Table 1-3. ASSESSMENT OF ENVIRONMENTAL, ENERGY, AND ECONOMIC IMPACTS FOR EACH REGULATORY ALTERNATIVE CONSIDERED FOR EXISTING TANKS[a]

Administrative alternative	Air impact	Water impact	Solid waste impact	Energy impact	Economic impact
Control option 0 (no additional standard)	-5**	0	0	0	0
Control option I	+1**	0	0	0	-1**
Control option II	+2**	0	0	0	-2**
Control option III	+3**	0	0	0	-2**
Control option IV(A)	+4**	0	0	0	-2**
Control option IV(B)	+4**	-2**	-1*	-1**	-3**
Control option V	+4**	-1**	0	-3**	-3**
Control option VI	+5**	+1**	0	0	-5**
Delayed Standard	-2*	0	0	0	+1*

[a] KEY:
+ Beneficial impact
- Adverse impact
0 No impact
1 Negligible impact
2 Small impact
3 Moderate impact
4 Large impact
5 Very large impact
* Short term impact
** Long term impact
*** Irreversible impact

Table 1-4. ASSESSMENT OF ENVIRONMENTAL, ENERGY, AND ECONOMIC IMPACTS FOR EACH REGULATORY ALTERNATIVE CONSIDERED FOR NEW TANKS[a]

Administrative alternative	Air impact	Water impact	Solid waste impact	Energy impact	Economic impact
Control option 0 (no additional standard)	-5**	0	0	0	0
Control option I	+1**	0	0	0	-1**
Control option II	+3**	0	0	0	-2**
Control option III	+4**	0	0	0	-2**
Control option IV(A)	+4**	-2**	-1*	-1**	-3**
Control option IV(B)	+4**	-1**	0	-3**	-3**
Control option V	+5**	+1**	0	0	-5**
Delayed standard	-2*	0	0	0	+1*

[a] KEY:
+ Beneficial impact
- Adverse impact
0 No impact
1 Negligible impact

2 Small impact
3 Moderate impact
4 Large impact
5 Very large impact

* Short term impact
** Long term impact
*** Irreversible impact

1.3 ECONOMIC IMPACT

Except for the control options which would prohibit the storage of benzene in tanks (Options V and VI for new and existing tanks, respectively) and those which would require that each tank be fitted to a vapor control system (Options IV and V for new and existing tanks, respectively) the economic impacts are inconsequential, resulting in a maximum price increase of benzene of only 0.104 percent. The impacts associated with the options which would require the use of vapor control systems are also quite small; however, in comparison with less stringent options, the vapor control options are much more expensive, costing roughly three to ten times as much. The options which would prohibit the storage of benzene in tanks would result in the most severe economic impacts to industry of any of the options considered.

1.3 ECONOMIC IMPACT

Except for the control options which would prohibit the storage of benzene in tanks (Options V and VI for new and existing tanks, respectively) and those which would require that each tank be fitted to a vapor control system (Options IV and V for new and existing tanks, respectively) the economic impacts are inconsequential, resulting in a maximum price increase of benzene of only 0.104 percent. The impacts associated with the options which would require the use of vapor control systems are also quite small; however, in comparison with less stringent options, the vapor control options are much more expensive, costing roughly three to ten times as much. The options which would prohibit the storage of benzene in tanks would result in the most severe economic impacts to industry of any of the options considered.

2. INTRODUCTION

2.1 BACKGROUND

On October 10, 1979, the Environmental Protection Agency proposed "Policies and Procedures for Identifying, Assessing, and Regulating Airborne Substances Posing a Risk of Cancer" (44 FR 58642). All standards for carcinogens regulated under Section 112 of the Clean Air Act are being developed in accordance with these proposed policies and procedures. The following is a section quoted from the "Policies and Procedures," which describes the procedures for establishing standards once the decision has been made to regulate a pollutant.

> (2) The Proposed EPA Approach
>
> The standard-setting policy proposed today requires, as a minimum, the use of "best available technology" (BAT) to control emissions from source categories presenting significant risks to public health. The policy would also require additional controls, as necessary, to eliminate "unreasonable residual risks" remaining after the use of best available technology. This approach is a judgmental one, designed to protect the public health with an ample margin of safety from risks associated with exposure to airborne carcinogens. The implementing procedure described below puts prime emphasis on public health, consistent with section 112, but permits consideration of economic impacts and benefits of the activity in setting standards for each source category. Uncertainties in the assessments of risks, costs, and potential benefits, as well as the distributional (equity) problems of various situations, would also be considered in setting standards.
>
> (a) Source Categories Regulated
>
> The first step in establishing standards and requirements for pollutants listed under section 112 under this proposed policy is the determination of which categories of sources emitting the pollutants will be regulated, and in what order regulations will be developed. Although a pollutant may

have been listed because emissions from a particular source category pose a significant risk, other source categories may also emit the pollutant in lesser amounts. This may occur, for example, because the sources process very little of the substance, because the substance is present in only trace amounts in the sources' raw materials, or because sources have installed adequate controls on their own initiative or in response to other regulatory requirements.

The Administrator will therefore propose regulations only for those source categories which may pose significant risks to public health. The determination of whether a source category emitting a listed pollutant poses a significant risk will be made on essentially the same basis as the listing decision, except that the more detailed exposure analysis and risk assessment then available will be used in lieu of the preliminary information used in the listing decision. As in the listing decision, the risk assessment will be used to indicate the existence of a significant risk where the exposure analysis alone is insufficient, but will not be used as evidence that a significant risk does not exist where the exposure analysis indicates to the contrary.

(b) Priorities for the Development of Standards

EPA anticipates that a substantial number of substances will be listed as carcinogenic air pollutants under section 112 in the near future. It is also likely that many of these substances will be emitted in significant quantities from more than one source category. As a result, EPA will need to develop emission standards and other requirements for a large number of source categories emitting these substances. At least until generic standards can be developed for large groups of these sources, the resources that would be necessary to complete this task immediately far exceed those available to EPA for this purpose. Today's proposal therefore provides for the assignment of priorities to significant source categories for the development of these regulations, through publicly stated criteria and announced decisions.

Under today's proposal, source categories posing significant risks will be assigned priority status (high, medium, or low) for further regulatory action (beyond generic standards) on the basis of: (1) the magnitude of projected total excess cancer incidence associated with current and future source emissions; (2) magnitude of cancer risks for the most exposed individuals; (3) ease of expeditious standards development and implementation; and (4) feasibility of significant improvements in controls. In addition, significant sources of more than one carcinogen may be given priority over single-pollutant sources, based on the sum of risks from the emitted substances.

A high priority will be assigned, for example, to a source category constituting an important problem requiring immediate attention, or where risks are somewhat lower but an appropriate regulatory solution is both feasible and readily available. Source categories assigned medium priority will generally be those that present lower risks and will be scheduled for standard development as resources become available. Lower risk source categories for which the extent of feasible control may be substantially limited will be assigned low priority for regulation development. Assignment to the low priority category will generally mean that active development of regulations will not begin until there is some change in the factors which led to the assignment, or until higher priority actions have been completed.

(c) Regulatory Options Analysis

EPA will perform detailed analyses to identify alternative, technologically feasible control options and the economic, energy, and environmental impacts that would result from their application. Where substitution is determined to be a feasible option, the benefits of continued use of the substance or process will be considered. These analyses will rely primarily on the procedures and techniques employed by EPA for developing New Source Performance Standards under section 111 of the Act.

The identification of feasible control options will initially survey the existing control devices at the sources within a particular category to determine the best controls currently in use. The potential emission points of the listed pollutant at a particular kind of facility will also be identified, as will possible emissions of carcinogens other than the specific one under study. EPA will, in addition, examine the applicability of available technologies which are not currently used by the industry to control the pollutant of concern (technology transfer) but which have been demonstrated in pilot tests or other industrial applications. Finally, the availability and adequacy of substitutes which would eliminate some or all emissions of the pollutant will be assessed.

Once the technologically feasible control alternatives, which may range from no further control to a complete ban on emissions, have been identified, the environmental, economic and energy impacts of these options will be determined. Considerations in these impact assessments will include for each option: the number of plant closures predicted and the direct impact on employment and end product prices; the impact on growth and expansion of the industry; the resulting changes in profitability; capital availability for control equipment; the impacts from the availability of substitute products and foreign imports; the potential increases in national energy consumption; and the impacts on other environmental media including increased water pollution and solid waste disposal. On the basis of these assessments, one of the control options identified will be designated as the "best available technology" for the control of emissions from the sources in the category. This level of control will be that technology, which in the judgment of the Administrator, is the most advanced level of control adequately demonstrated, considering economic, energy, and environmental impacts.

The control level designated "best available technology" may be different for new and existing facilities in a category. For practical purposes, this level of control for new sources will, as a minimum, be equivalent to that which would be selected as the basis for a New Source Performance Standard (NSPS) under section III. The requirement of "best available technology" for new sources would consider "economic feasibility" and would not preclude new construction.

The selection of BAT for existing sources may require consideration of the technological problems associated with retrofit and related differences in the economic, energy, and environmental impacts. In practice, BAT for existing sources would consider economic feasibility and would not exceed the most advanced level of technology that at least most members of an industry could afford without plant closures.

(d) Minimum Requirements for Existing Sources

Final section 112 standards will require existing sources in any regulated source category, as a minimum, to limit their emissions to the levels corresponding to the use of "best available technology." This requirement is based on the Administrator's judgment that any risks that could be avoided through the use of these feasible control measures are unreasonable. Whether BAT controls are sufficient to protect public health will be determined by a subsequent evaluation of the remaining risks.

(e) Determination of Unreasonable Residual Risk For Existing Sources

Following the identification of BAT for existing sources, the quantitative risk assessment described earlier will be used to determine the risks remaining after the application of BAT to the source category. If the residual risks are not judged by the Administrator to be unreasonable, further controls would not be required. If, however, there is a finding of unreasonable residual risk, a more stringent alternative would be required. Among the possible alternatives would be the immediate application of more restrictive emission standards, including those based on more extensive use of substitutes, and scheduled or phased reductions in permissible emissions. The alternative selected would be that necessary, in the Administrator's judgment, to eliminate the unreasonable residual risks.

Given the differences in the degree of certainty in risk estimates, in the numbers of people exposed, in benefits, in the distribution of risks and benefits, in the costs of controls, in the availability of substitutes, and in other relevant factors, it is not possible to state any precise formula for determining unreasonable residual risk. The determination will necessarily be a matter of judgment for each category involved. Nevertheless, the process followed and the various factors involved can be outlined.

The determination of unreasonable residual risk will be based primarily on public health, and will require protection with an ample margin of safety. To the extent possible, quantitative or qualitative estimates of various factors will be made for purposes of comparison. Among these are: (1) the range of total expected cancer incidence and other health effects in the existing and future exposed populations through the anticipated operating life of existing sources; (2) the range of health risks to the most exposed individuals; (3) readily identifiable benefits of the substance or activity; (4) the economic impacts of requiring additional control measures; (5) the distribution of the benefits of the activity versus the risks it causes; and (6) other possible health and environmental effects resulting from the increased use of substitutes.

3. INDUSTRY DESCRIPTION AND MODEL PLANTS

3.1 INTRODUCTION

Generally, benzene storage tanks can be found in three types of facilities: (1) benzene producing facilities such as refineries; (2) benzene consuming facilities such as chemical plants; and (3) bulk storage terminals. Of the 143 facilities which are known to store benzene,[a] 62 (43 percent) are benzene producers, 77 (54 percent) are benzene consumers, and 4 (3 percent) are bulk storage terminals. Benzene storage tanks used at coke oven byproduct facilities have been excluded from the tank inventory because a separate standard is being developed for these tanks.

Three types of tanks are used for benzene storage: fixed-roof tanks, external floating-roof tanks, and internal floating-roof tanks. A detailed description of these types of tanks and their sources of emissions follows. In addition, the methods for estimating the emissions from tanks, as well as the estimated national baseline emissions, are presented.

3.2 BENZENE STORAGE TANKS

Based on information obtained from the Chemical Economics Handbook,[1] an Environmental Protection Agency (EPA) draft report,[2] responses to Section 114 letters, and other correspondence, there are 494 benzene storage tanks nationwide.[a] Of these, 177 are fixed-roof tanks, 28 are external floating-roof tanks, and 289 are internal floating-roof tanks. These represent about 36 percent, 6 percent, and 58 percent, respectively, of the 494 tanks.

3.2.1 Types of Storage Tanks

3.2.1.1 Fixed-Roof Tanks. Of presently employed tank designs, the fixed-roof tank is the least expensive to construct and is generally considered as the minimum acceptable tank for the storage of petroleum liquids such as benzene. A typical fixed-roof tank, which is shown in Figure 3-1, consists of a cylindrical steel shell with a cone- or dome-shaped roof which is permanently affixed to the tank shell. A breather valve (pressure-vacuum valve), which is commonly installed on many fixed-roof tanks, allows the tank to operate at a slight internal pressure or vacuum. Because this valve prevents the release of vapors only during very small changes in temperature, barometric pressure, or liquid level, the emissions from a fixed-roof tank can be appreciable.

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[a] Base year 1979.

3.2.1.2 External Floating-Roof Tanks. A typical external floating-roof tank is shown in Figure 3-2. This type of tank consists of a cylindrical steel shell equipped with a deck or roof which floats on the surface of the stored liquid, rising and falling with the liquid level. The liquid surface is completely covered by the floating roof except in the small annular space between the roof and the tank wall. A seal attached to the roof contacts the tank wall (except for small gaps in some cases) and covers the remaining area. The seal slides against the tank wall as the roof is raised or lowered.

3.2.1.3 Internal Floating-Roof Tanks. An internal floating-roof tank has both a permanently-affixed roof and a roof that floats on the liquid surface (contact roof) or is supported on pontoons several inches above the liquid surface (noncontact roof) inside the tank. (Typical contact and noncontact internal floating-roof tanks are shown in Figure 3-3a and 3-3b, respectively.) The internal floating roof rises and falls with the liquid level. Contact-type roofs include: (1) aluminum sandwich panel roofs with a honeycombed aluminum core floating in contact with the liquid, and (2) pan-type steel roofs floating in contact with the liquid with or without the aid of pontoons. Noncontact-type roofs typically consist of an aluminum deck on an aluminum grid framework supported above the liquid surface by tubular aluminum pontoons. Both types of internal floating roofs, like external floating roofs, commonly incorporate flexible perimeter seals or wipers which slide against the tank wall as the roof moves up and down. In addition, circulation vents and an open vent at the top of the fixed roof are provided to minimize the possibility of

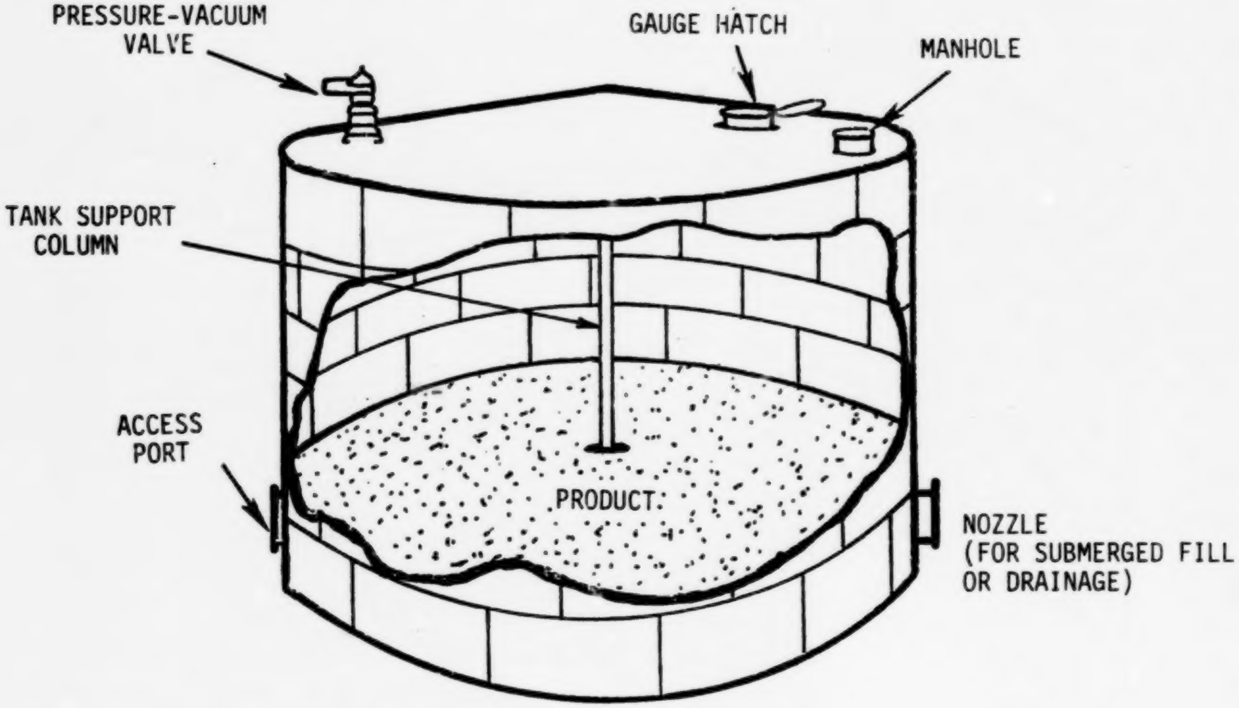

PRESSURE-VACUUM VALVE
GAUGE HATCH
MANHOLE
TANK SUPPORT COLUMN
ACCESS PORT
PRODUCT
NOZZLE (FOR SUBMERGED FILL OR DRAINAGE)

Figure 3-1. Typical fixed-roof tank.[3]

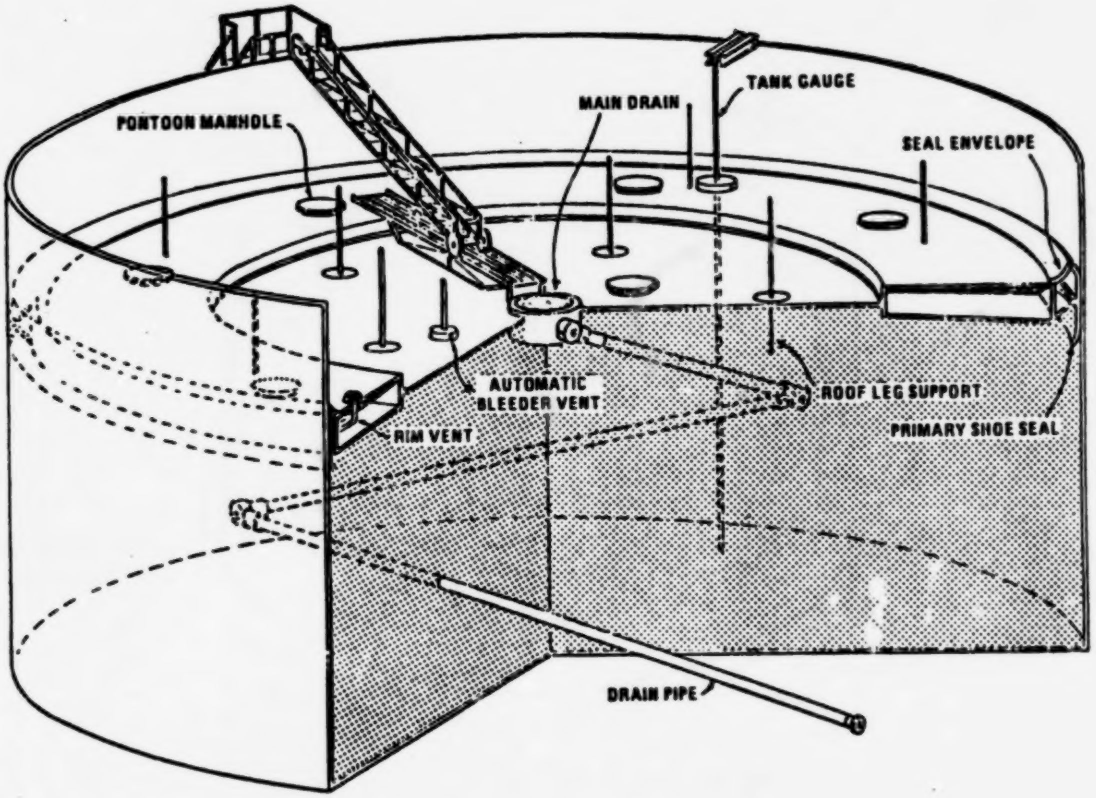
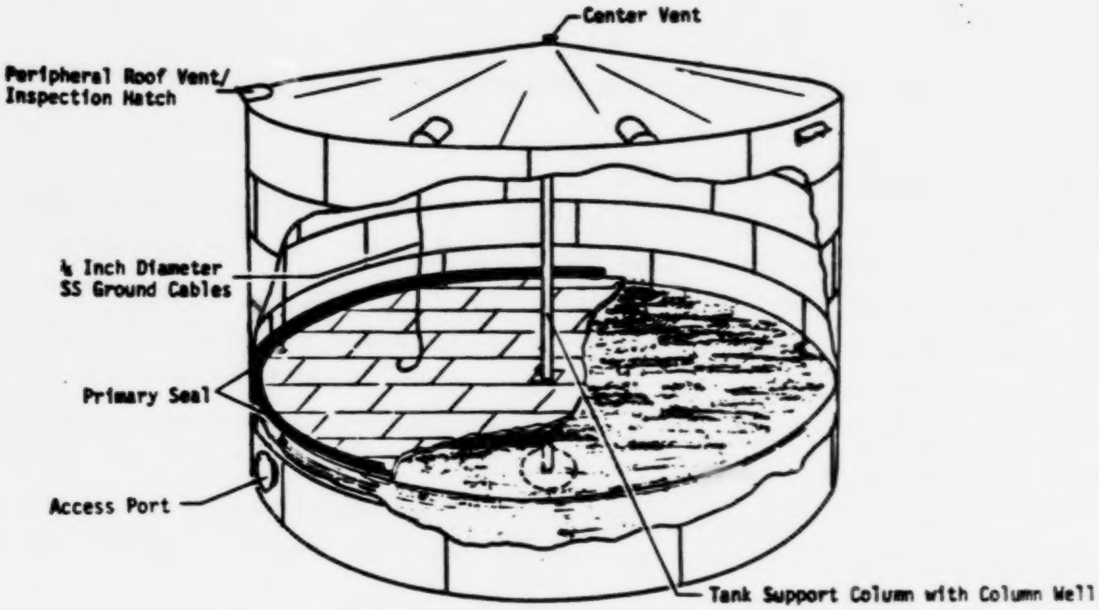
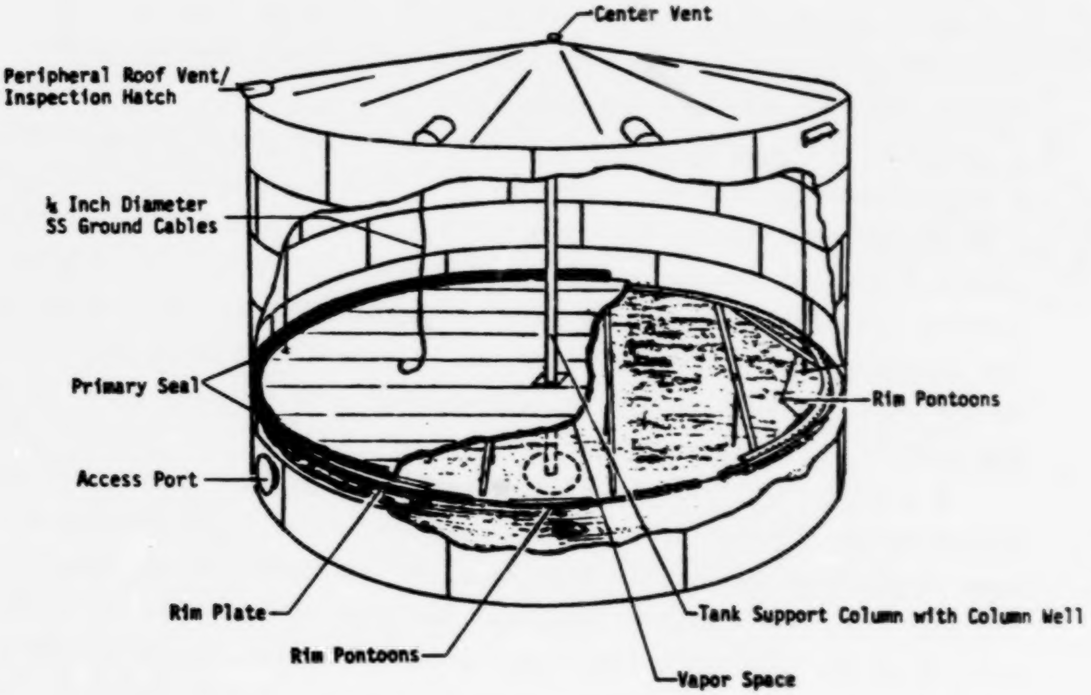

PONTOON MANHOLE
MAIN DRAIN
TANK GAUGE
SEAL ENVELOPE
AUTOMATIC BLEEDER VENT
ROOF LEG SUPPORT
PRIMARY SHOE SEAL
RIM VENT
DRAIN PIPE

Figure 3-2. External floating-roof tank.[4]


Center Vent
Peripheral Roof Vent/
Inspection Hatch
¼ Inch Diameter
SS Ground Cables
Primary Seal
Access Port
Tank Support Column with Column Well

a. Contact internal floating roof.


Center Vent
Peripheral Roof Vent/
Inspection Hatch
¼ Inch Diameter
SS Ground Cables
Primary Seal
Access Port
Rim Pontoons
Rim Plate
Rim Pontoons
Tank Support Column with Column Well
Vapor Space

b. Noncontact internal floating roof.

Figure 3-3(a,b). Internal floating-roof tanks.[3]

hydrocarbon vapors accumulating in concentrations approaching the flammable range.

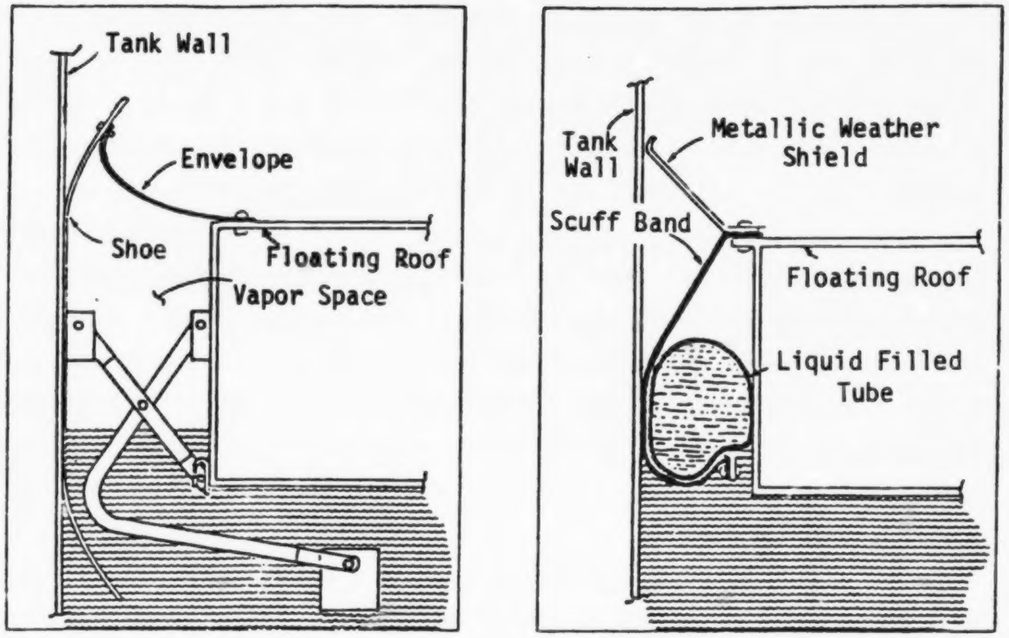
3.2.2 Types of Primary Seals

3.2.2.1 External Floating Roofs. There are basically three types of primary seals used on external floating roofs: mechanical shoe seals, liquid-filled seals, and resilient foam-filled seals. Although there are other designs, these three comprise the vast majority of primary seals in use today. A primary seal serves as a vapor conservation device by closing the annular vapor space between the edge of the floating roof and the tank wall.

3.2.2.1.1 Mechanical shoe seal. A mechanical shoe seal, otherwise known as a metallic shoe seal (Figure 3-4a), is characterized by a 75- to 130-cm high (30- to 51-inch high) metallic sheet (the "shoe") held against the vertical tank wall. The shoe is connected by braces to the floating roof and is held tightly against the wall by springs or weighted levers. A flexible coated fabric (the "envelope") is suspended from the shoe seal to the floating roof to form a gastight cover over the annular space between the roof and the primary seal.

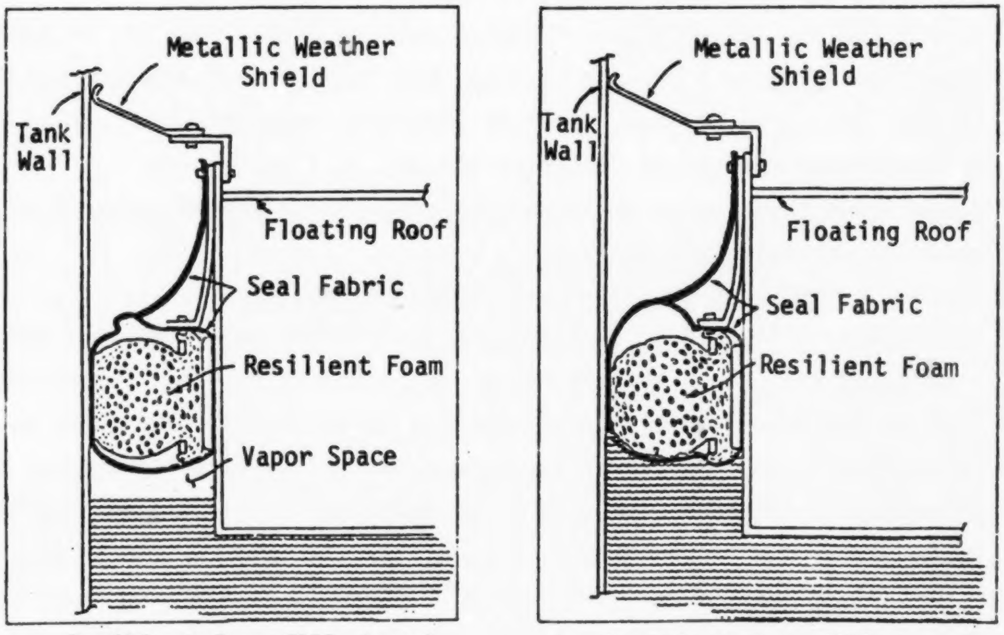
3.2.2.1.2 Liquid-filled seal. A liquid-filled seal (Figure 3-4b) may be a tough fabric band or envelope filled with a liquid, or it may be a 20- to 25-cm (8- to 10-inch) diameter flexible polymeric tube filled with a liquid and sheathed with a tough fabric scuff band. The liquid is commonly a petroleum distillate or other liquid which will not contaminate the stored product if the tube ruptures. Liquid-filled seals are mounted on the product liquid surface (liquid-mounted) with no vapor space below the seal.

3.2.2.1.3 Resilient foam-filled seal. A resilient foam-filled seal is similar to a liquid-filled seal except that a resilient foam log is used in place of the liquid. Because of the resiliency of the foam log, the seal can adapt itself to some tank shell out-of-roundness and deformations of the tank wall The foam log may be mounted several inches above the liquid surface (vapor-mounted) or on the liquid surface (liquid-mounted). Typical vapor-mounted and liquid-mounted foam-filled seals are shown in Figures 3-4c and 3-4d, respectively.


Tank Wall
Envelope
Shoe
Floating Roof
Vapor Space
Tank Wall
Metallic Weather Shield
Scuff Band
Floating Roof
Liquid Filled Tube

a. Metallic shoe seal.

b. Liquid-filled seal with weather-shield.


Metallic Weather Shield
Tank Wall
Floating Roof
Seal Fabric
Resilient Foam
Vapor Space
Metallic Weather Shield
Tank Wall
Floating Roof
Seal Fabric
Resilient Foam

c. Resilient foam-filled seal (vapor-mounted) with weather seal.

d. Resilient foam-filled seal (liquid-mounted) with weather seal.

Figure 3-4(a-d). Typical primary seals on external floating roofs.[4]

3.2.2.1.4 Weather shield. A weather shield (Figures 3-4b, 3-4c, and 3-4d) may be installed over the primary seal to protect it from deterioration caused by debris and exposure to the elements. Typically, a weather shield is an arrangement of overlapping thin metallic sheets pivoted from the floating roof to ride against the tank wall.

3.2.2.2 Internal Floating Roofs. Internal floating roofs typically incorporate one of two types of flexible, product-resistant primary seals: either resilient foam-filled seals or wiper seals. Similar to the types of seals employed on external floating roofs, each of these seals closes the annular vapor space between the edge of the floating roof and the tank wall. In addition, each seal compensates for tank wall irregularities and, thus, allows the roof to move freely up and down in the tank without binding.

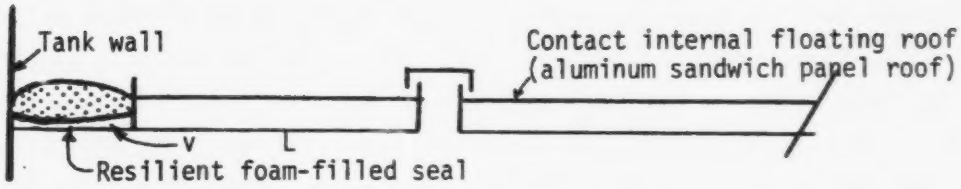
3.2.2.2.1 Resilient foam-filled seal. A resilient foam-filled seal used on an internal floating roof consists of a tough fabric envelope stuffed with open cell foam. This type of seal can either be vapor-mounted (Figure 3-5a) or liquid-mounted (3-5b).

3.2.2.2.2 Wiper seal. A closed-cell, or other type of elastomeric wiper seal (Figure 3-5c) can also be used to close the annular vapor space. This type of seal, which is generally vapor-mounted, can either be continuous around the circumference of the floating roof (continuous-type seal), or it can consist of overlapping segments of seal material (shingle-type seal).

3.2.3 Storage Tank Emissions and Emissions Equations

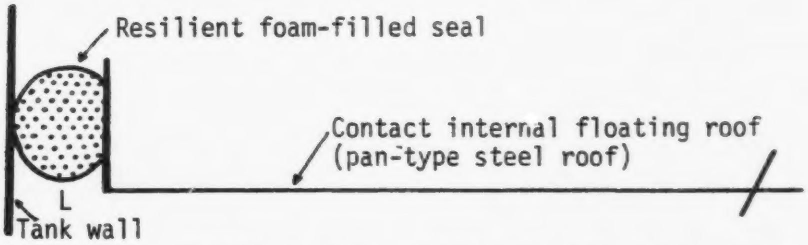
3.2.3.1 Fixed-Roof Tank Emissions. The two major types of emissions from fixed-roof tanks are breathing loss and working loss. Breathing loss is the expulsion of vapor from a tank due to vapor expansion and contraction resulting from diurnal temperature and barometric pressure changes. It occurs in the absence of any liquid level change in the tank.

Filling loss is associated with an increase of the liquid level in the tank. The vapors are expelled from the tank when the pressure inside the tank exceeds the relief pressure as a result of filling. Emptying loss occurs when air drawn into the tank during liquid removal becomes


Tank wall
Contact internal floating roof
(aluminum sandwich panel roof)
v
L
Resilient foam-filled seal

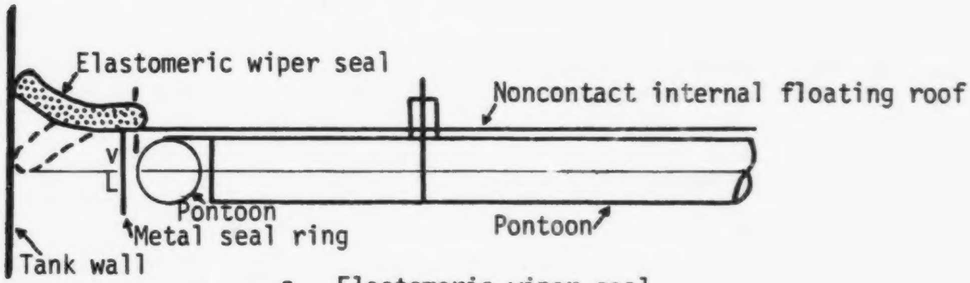
a. Resilient foam-filled seal (vapor-mounted).

Note: v - vapor
L - liquid


Resilient foam-filled seal
Contact internal floating roof
(pan-type steel roof)
L
Tank wall

b. Resilient foam-filled seal (liquid-mounted).

Note: v - vapor
L - liquid


Elastomeric wiper seal
Noncontact internal floating roof
v
L
Pontoon
Metal seal ring
Pontoon
Tank wall

c. Elastomeric wiper seal.

Note: v - vapor
L - liquid

Figure 3-5(a-c). Typical primary seals on internal floating roofs.[3]

saturated with hydrocarbon vapor and expands, thus exceeding the capacity of the vapor space. The combined loss from filling and emptying is called "working loss."

3.2.3.1.1 Fixed-roof tanks emissions equations. The AP-42 emissions equations for breathing and working losses were used to estimate benzene emissions from fixed-roof tanks.[5] However, breathing losses calculated using these equations were discounted by a factor of four in light of test results released by EPA,[6] the Western Oil and Gas Association (WOGA),[7] and the German Society for Petroleum Science and Carbon Chemistry (DGMK).[8] These results, which are discussed in Appendix C, indicate that AP-42 tends to overestimate the actual breathing losses from fixed-roof tanks by roughly a factor of four. The working losses have not been adjusted, because initial testing indicates that AP-42 is fairly accurate for estimating these losses. The equations used to estimate emissions from fixed-roof tanks follow:

$$L_T = L_B + L_W \tag{3-1}$$

$$L_B = 9.15 \times 10^{-6} M_V \left(\frac{P}{14.7 - P}\right)^{0.68} D^{1.73} H^{0.51} \Delta T^{0.5} F_p C \tag{3-2}$$

$$L_W = 1.09 \times 10^{-8} M_V P K_n V N \tag{3-3}$$

where, L_T = total loss (Mg/yr)
L_B = breathing loss (Mg/yr)
L_W = working loss (Mg/yr)
M_V = molecular weight of product vapor (lb/lb mole); 78.1 lb/lb mole for benzene
P = true vapor pressure of product (psia); 1.5 psia assumed for this study
D = tank diameter (ft)
H = average vapor space height = tank height/2 (ft)
ΔT = average diurnal temperature change in °F; 15°F assumed for this study
F_p = paint factor; 1.0 for clean white paint was used
C = tank diameter factor;
for diameter $\geq$ 30 feet, $C = 1$
for diameter < 30 feet, $C = 0.0771\,D - 0.0013\,D^2 - 0.1334$

N = number of turnovers per year

K_n = turnover factor;

for number of turnovers, $N \geqq 36$, $K_n = \frac{180 + N}{6N}$

for number of turnovers, $N < 36$, $K_n = 1$

V = tank capacity (gal).

3.2.3.2 Internal and External Floating-Roof Tank Emissions. Standing-storage loss, which results from causes other than breathing or change in the liquid level, constitutes one source of emissions from internal and external floating-roof tanks. The largest potential source of this loss is from gaps between the seal and the tank wall. As a result of these gaps, some portion of the liquid surface is exposed to the atmosphere. When air flow across the tank creates pressure differences around the floating roof, air flows into the annular vapor space on the leeward side and an air-vapor mixture flows out on the windward side.

Withdrawal loss is another source of emissions from internal and external floating-roof tanks. Withdrawal loss is the vaporization of liquid from a wetted tank wall when a floating roof is lowered by withdrawal of liquid.

Fitting loss, which is a result of penetrations in the roof for deck fittings, roof column supports, or other openings, can also account for significant emissions from internal floating-roof tanks. However, this loss is not a significant source of emissions from external floating-roof tanks.

3.2.3.2.1 Internal and external floating-roof tank emissions equations. Benzene emissions from external floating-roof, noncontact internal floating-roof, and contact internal floating-roof storage tanks were estimated using equations based on a pilot test tank study conducted for EPA.[9] Descriptions of the tank, test methods, and data obtained from this study are presented in Appendix C.

From the equations presented below, it was possible to estimate the total evaporation loss (L_T), which is the sum of the withdrawal loss (L_{WD}), the seal loss (L_S), and the fitting loss (L_F).

$$L_T = L_{WD} + L_S + L_F \qquad (3\text{-}4)$$

$$L_{WD} = \frac{0.943\ QCW_L}{2205D} \tag{3-5}$$

$$L_S = K_S\ V^n\ M_V\ D \left(\frac{\frac{P}{(14.7)}}{[1 + (1 - \frac{P}{14.7})^{0.5}]^2} \right) \frac{1}{2205} \tag{3-6}$$

$$L_F = NK_F\ V^m\ M_V \left(\frac{\frac{P}{(14.7)}}{[1 + (1 - \frac{P}{14.7})^{0.5}]^2} \right) \frac{1}{2205} \tag{3-7}$$

where, L_T = total loss (Mg/yr)
L_{WD} = withdrawal loss (Mg/yr)
L_S = seal loss (Mg/yr)
L_F = fitting loss (Mg/yr)
M_V = molecular weight of product vapor (lb/lb mole); 78.1 lb/lb mole for benzene
P = true vapor pressure of product (psia); 1.5 psia assumed for this study
D = tank diameter (ft)
W_L = density of product (lb/gal); 7.37 lb/gal for benzene
V = average wind speed for the tank site (mph); 10 mph average wind speed assumed for this study
Q = product average throughput (bbl/yr); tank capacity (bbl/turnover) x turnovers/yr
K_S = seal factor; see Table 3-1
K_F = fitting factor; see Table 3-2
n = seal wind speed exponent; see Table 3-1
m = fitting wind speed exponent; see Table 3-2
C = product withdrawal shell clingage factor (bbl/(ft^2 x 10^3)); use 0.0015 bbl/(ft^2 x 10^3) for benzene in a welded steel tank with light rust
N = fitting multiplier; see Table 3-3.

Table 3-1. EMISSION FACTORS K_S AND n[9]

Roof and seal combinations	K_S[a]	n[b]
Contact internal floating roof		
Liquid-mounted primary seal only	12.7	0.4
Liquid-mounted primary seal and continuous secondary seal	3.6	0.7
Noncontact internal floating roof with vapor-mounted primary and secondary seals	10.3	1.0
External floating roof		
Primary seal only	48.6	0.7
Primary and secondary seals	57.7	0.2

[a] K_S - seal factor.

[b] n - seal wind speed exponent.

Table 3-2. SUMMARY OF EMISSION FACTORS K_F AND m FOR FLOATING ROOFS[9]

Case number	Roof description	K_F[a]	m[b]
1	Contact internal floating roof	132	0
2	Noncontact internal floating roof	309	0.3
3	External floating roof	0	0

[a] K_F - fitting factor.

[b] m - fitting wind speed exponent.

Table 3-3. FITTING MULTIPLIERS[9]

D tank diameter (ft)	N fitting multiplier
$D <$	0.5
$20 \leq D < 75$	1
$75 \leq D < 100$	2
$100 \leq D < 120$	3
$125 \leq D < 150$	4
$150 \leq D < 175$	5
$175 \leq D < 200$	6

3.3 BASELINE EMISSIONS

The baseline assumptions and the national baseline benzene emissions from storage tanks are discussed in this section. In addition, the model plants used for estimating the emissions and the number of each type of model plant are presented.

3.3.1 Development of the Baseline

3.3.1.1 Existing Tanks. The baseline for existing tanks is the Control Techniques Guideline (CTG) for fixed-roof tanks (Control of Volatile Organic Emissions from Storage of Petroleum Liquids in Fixed-Roof Tanks) issued in December, 1977 (EPA-450/2-77-036).[3] This CTG recommends that all fixed-roof tanks which have capacities greater than 150,000 liters and which store volatile petroleum liquids (true vapor pressure greater than 10.5 kPa or 1.52 psia) have internal floating roofs.[3] Storage tanks with capacities less than 150,000 liters, which are generally fixed-roof tanks, would be unaffected by the CTG. Because cost data indicate that a noncontact internal floating roof is generally cheaper than a contact internal floating roof of the same size, the tanks affected by the CTG are assumed to have noncontact internal floating roofs.

In addition, it is assumed that the model plants being developed would most likely be located in nonattainment areas for ozone. This assumption is made because 115 (about 80 percent) of the 143 benzene storage facilities are located in nonattainment areas for ozone. Each area which is classified as an ozone nonattainment area is required to adopt a standard for fixed-roof tanks at least as effective in reducing emissions as the fixed-roof tank CTG.

3.3.1.2 New Tanks. The baseline for new tanks is the New Source Performance Standard (NSPS) for petroleum liquid storage tanks ("Petroleum Liquid Storage Vessels; Standards of Performance for New Stationary Sources") promulgated on April 4, 1980 (45 FR 23374). This NSPS requires that each benzene storage tank which is constructed after May 18, 1978, and which has a capacity greater than about 150,000 liters, have either (1) an external floating roof with primary and secondary seals, or (2) a fixed roof and an internal floating roof. (The use of secondary seals as an emissions control technique is discussed in Chapter 4.) Storage tanks with capacities less than 150,000 liters, which are generally fixed-roof tanks, would be unaffected by the NSPS.

3.3.2 Development of Model Plants

In order to develop a representative set of model plants for evaluating the environmental, energy, and economic impacts of controlling benzene emissions from benzene storage tanks, surveys were conducted of facilities having benzene storage tanks.[1,2,10,11,12] These facilities included benzene producers, consumers, and bulk storage terminals. The surveys were instituted to obtain information on the benzene throughput, types and sizes of benzene storage tanks, and types of control equipment at each facility.

Using rated plant capacities from the Chemical Economics Handbook,[1] each of the 62 producers listed in Table 3-4 was classified as either a large benzene producer or a small benzene producer. Each producer with a rated capacity above the median capacity for all the producers was classified as a large producer, while each producer with a rated capacity below the median was classified as a small producer.

Subsequently, information acquired from the survey of producers, consumers, and bulk storage terminals storing benzene was used to estimate the number, types, and sizes of benzene storage tanks at a typical producer, consumer, and bulk storage terminal, respectively. For those storage tanks for which only tank capacity was given, the diameter and height were estimated using existing data from the survey as well as standardized tables of capacity versus tank dimensions. In addition, for those storage tanks listed only as floating-roof tanks (i.e., no distinction made between internal or external floating roof), it was assumed that all were internal floating-roof tanks. This assumption was based on information which indicated that 87 percent of the floating-roof tanks surveyed were internal floating-roof tanks. The survey also indicated that approximately half of these tanks were contact internal floating-roof tanks and half were noncontact internal floating-roof tanks.

The model plants developed from this analysis and from a consideration of the baselines for new and existing tanks are presented in Table 3-5. Using these models and the emissions equations presented in

Table 3-4. PLANTS WITH BENZENE STORAGE TANKS[1,2,10,11,12]

I. PRODUCERS

Region/Company	Size[a]	State	City	County	AQCR[b]	Oxidant attainment status[c]
Region II						
Exxon	S	NJ	Linden	Union	043	NA
Texaco	L	NJ	Westville	Glouchester	045	NA
Ashland Oil	S	NY	N. Tonawanda	Niagara	162	NA
Commonwealth Oil	L	PR	Penuelas		244	A
Phillips	L	PR	Guayama		244	A
Amerada Hess	L	VI	St. Croix		247	A
Region III						
Getty	S	DE	Delaware City	New Castle	045	NA
Gulf Oil	L	PA	Philadelphia	Philadelphia	045	NA
Standard Oil	S	PA	Marcus Hook	Delaware	151	NA
Sun Oil	S	PA	Marcus Hook	Delaware	151	NA
Region IV						
Triangle Refineries	S	AL	Mobile	Mobile	005	NA
Ashland Oil	L	KY	Catlettsburg	Boyd	103	NA
Chevron	S	MS	Pascagoula	Jackson	005	A
Region V						
Shell Oil	L	IL	Wood River	Madison	070	NA
Union Oil	S	IL	Lemont	Cook	067	NA
DOW Chemical	L	MI	Bay City	Bay	122	NA
Sun Oil	L	OH	Toledo	Lucas	124	NA
Region VI						
Cities Services	S	LA	Lake Charles	Calcasieu	106	NA
DOW Chemical	L	LA	Plaquemine	Iberville	106	NA
Exxon	L	LA	Baton Rouge	E. Baton Rouge	106	NA
Gulf Oil	L	LA	Belle Chasse (Alliance)	Plaquemines	106	A-UNCL
Pennzoil United	L	LA	Shreveport	Caddo	022	NA
Tenneco	S	LA	Chalmette	St. Bernard	106	NA
Union Carbide	L	LA	Taft	St. Charles	106	NA
Sun Oil	S	OK	Tulsa	Tulsa	186	NA
American Petrofina	S	TX	Port Arthur	Jefferson	106	NA
Amoco (Standard)	L	TX	Texas City	Galveston	216	NA
Atlantic Richfield	L	TX	Channelview	Harris	216	NA
Atlantic Richfield	L	TX	Houston	Harris	216	NA
Champlin	S	TX	Corpus Christi	Nueces	214	NA
Charter International	S	TX	Houston	Harris	216	NA
Coastal States	L	TX	Corpus Christi	Nueces	214	NA
Cosden (American Petrofina)	L	TX	Big Spring	Howard	218	A-UNCL
Crown Central	S	TX	Houston	Harris	216	NA
Crown Central	S	TX	Pasadena	Harris	216	NA
DOW Chemical	L	TX	Freeport	Brazoria	216	NA
Exxon	L	TX	Baytown	Harris	216	NA
Gulf Oil	L	TX	Port Arthur	Jefferson	106	NA
Howell	S	TX	San Antonio	Bexar	217	NA
Independent Refining	S	TX	Winnie	Chambers	216	NA

(continued)

Table 3-4. Continued

Region/Company	Size[a]	State	City	County	AQCR[b]	Oxidant attainment status[c]
Kerr-McGee	S	TX	Corpus Christi	Nueces	214	NA
Marathon Oil	S	TX	Texas City	Galveston	216	NA
Mobil Oil	L	TX	Beaumont	Jefferson	106	NA
Monsanto	L	TX	Alvin	Brazoria	216	NA
Monsanto	L	TX	Texas City	Galveston	216	NA
Phillips	S	TX	Borger	Hutchinson	211	A-UNCL
Phillips	S	TX	Sweeny	Brazoria	216	NA
Quintana Howell	S	TX	Corpus Christi	Nueces	214	NA
Shell Oil	L	TX	Deer Park	Harris	216	NA
Shell Oil	S	TX	Odessa	Ector	218	NA
South Western	S	TX	Corpus Christi	Nueces	214	NA
Suntide (Sun)	L	TX	Corpus Christi	Nueces	214	NA
Texaco	L	TX	Port Arthur	Jefferson	106	NA
Union Pacific	S	TX	Corpus Christi	Nueces	214	NA
Union 76	S	TX	Nederland	Jefferson	106	NA
Region VII						
Getty	S	KS	El Dorado	Butler	099	A
Region IX						
Atlantic Richfield	S	CA	Carson (Wilmington)	Los Angeles	024	NA
Arco	S	CA	Long Beach	Los Angeles	024	NA
Chevron (Standard)	S	CA	El Segundo	Los Angeles	024	NA
Chevron (Standard)	S	CA	Richmond	Contra Costa	030	NA
Hawaiian Independent	S	HI	Honolulu	Honolulu	060	A-UNCL
Standard Oil	S	HI	Honolulu	Honolulu	060	A-UNCL

II. CONSUMERS

Region/Company	State	City	County	AQCR[b]	Oxidant attainment status[c]
Region II					
American Cyanamid	NJ	Bound Brook	Somerset	043	NA
DuPont	NJ	Gibbstown	Glouchester	045	NA
Exxon	NJ	Linden	Union	043	NA
Hummel Chemical	NJ	S. Plainfield	Middlesex	150	NA
Reichhold	NJ	Elizabeth	Union	043	NA
Standard Chlorine Chemical	NJ	Kearney	Hudson	150	NA
Tenneco	NJ	Fords	Middlesex	150	NA
Texaco	NJ	Westville	Glouchester	045	NA
Allied Chemical	NY	Syracuse	Onondaga	158	NA
ICC Industries	NY	Niagara Falls	Niagara	162	NA
Commonwealth Oil	PR	Penuelas		244	A
Corco Refining	PR	Talluboa Penuelas	Guayanilla	244	A
Phillips	PR	Guayana		244	A
Union Carbide	RP	Penuelas		244	A
Region III					
Standard Chlorine Chemical	DE	Delaware City	New Castle	045	NA

(continued)

Table 3-4. Continued

Region/Company	State	City	County	AQCR[b]	Oxidant attainment status[c]
Continental Oil	MD	Baltimore	Baltimore	115	NA
Atlantic Richfield	PA	Beaver Valley	Beaver	197	NA
Gulf Oil	PA	Philadelphia	Philadelphia	045	NA
Koppers	PA	Bridgeville	Allegheny	195	NA
Allied Chemical	WV	Moundsville	Marshall	235	A
American Cyanamid	WV	Willow Island	Pleasants	179	A
Ashland Oil	WV	Neal	Wayne	103	A
Mobil	WV	New Martinsville	Wetzel	235	A
PPG Industries	WV	New Martinsville	Wetzel	235	A
Union Carbide	WV	Charleston	Kanawha	232	NA
Region IV					
Reichhold	AL	Holt	Tuscaloosa	004	A-UNCL
Ashland Oil	KY	Catlettsburg	Boyd	103	NA
B. F. Goodrich	KY	Calvert City	Marshall	072	A-UNCL
G. A. F.	KY	Calvert City	Marshall	072	A-UNCL
Olin Corporation	KY	Brandenburg	Meade	078	A-UNCL
First Mississippi	MS.	Pascagoula	Jackson	005	A
Region V					
Clark Oil	IL	Blue Island	Cook	067	NA
Monsanto	IL	Sauget	St. Clair	070	NA
Reichhold Chemical	IL	East Morris	Grundy	067	NA
DOW Chemical	MI	Bay City	Bay	122	NA
DOW Chemical	MI	Midland	Midland	122	NA
Region VI					
Transvaal	AR	Jacksonville	Pulaski	016	NA
American Hoechst	LA	Baton Rouge	E. Baton Rouge	106	NA
COS-MAR	LA	Carville	Iberville	106	NA
Gulf Oil	LA	Donaldsonville	Ascension	106	NA
Gulf Oil	LA	Welcome	St. James	106	NA
Rubicon Chemicals	LA	Geismar	Ascension	106	NA
Sun Company	OK	Tulsa	Tulsa	186	NA
Amoco (Standard)	TX	Texas City	Galveston	216	NA
Atlantic Richfield	TX	Port Arthur	Jefferson	106	NA
Celanese	TX	Clear Lake	Harris	216	NA
Celanese	TX.	Pampa	Gray	211	A-UNCL
Coastal States	TX	Corpus Christi	Nueces	214	NA
Cosden (American Petrofina)	TX	Big Spring	Howard	218	A-UNCL
Denka (Petrotex)	TX	Houston	Harris	216	NA
DOW Chemical	TX	Freeport	Brazoria	216	NA
DuPont	TX	Beaumont	Jefferson	106	NA
El Paso Natural Gas	TX	Odessa	Ector	218	NA
Exxon	TX	Baytown	Harris	216	NA
Gulf Oil	TX	Port Arthur	Jefferson	106	NA
Marathon Oil	TX	Texas City	Galveston	216	NA
Mobil Oil	TX	Beaumont	Jefferson	106	NA
Monsanto	TX	Chocolate Bayou	Brazoria	216	NA
Monsanto	TX	Texas City	Galveston	216	NA
Oxirane	TX	Channelview	Harris	216	NA
Petro-Tex Chemical	TX	Houston	Harris	216	NA
Phillips	TX	Sweeny	Brazoria	216	NA

(continued)

Table 3-4. Concluded

Region/Company	State	City	County	AQCR[b]	Oxidant attainment status[c]
Standard Oil	TX	Texas City	Galveston	216	NA
Suntide (Sun)	TX	Corpus Christi	Nueces	214	NA
Texaco	TX	Port Arthur	Jefferson	106	NA
Texas Eastman	TX	Longview	Gregg	022	NA
Union Carbide	TX	Seadrift	Calhoun	214	A-UNCL
Union Pacific	TX	Corpus Christi	Nueces	214	NA
Union 76	TX	Nederland	Jefferson	106	NA
Region VII					
Getty	KS	El Dorado	Butler	099	A
Monsanto	MO	St. Louis	St. Louis	070	NA
Region IX					
Chevron	CA	El Segundo	Los Angeles	024	NA
Chevron	CA	Richmond	Contra Costa	030	NA
Diamond Shamrock	CA	Redwood City	San Mateo	030	NA
Specialty Organics	CA	Irwindale	Los Angeles	024	NA
Witco Chemical	CA	Los Angeles (Carson)	Los Angeles	024	NA
Montrose Chemical	NV	Henderson	Clark	013	NA

III. BULK STORAGE TERMINALS

Region/Company	State	City	County	AQCR[b]	Oxidant attainment status[c]
Region III					
Gordon Terminal Services Inc.	PA	McKees Rock	Alleghaney	197	NA
Region VI					
Amerada Hess Corp.	TX	Houston	Harris	216	NA
GATX Terminal Corp.	TX	Houston	Harris	216	NA
Petrounited Terminals Inc.	TX	Seabrook	Harris	216	NA

[a] S = small, L = large.

[b] AQCR = Air Quality Control Region.

[c] A = attainment, NA = nonattainment, A-UNCL = cannot be classified or better than national standards.

Table 3-5. MODEL BENZENE STORAGE PLANTS

Type of model plant	Tank dimensions, (diameter/height) (meters)	(feet)	Existing tank type[a] (CTG as baseline)	New tank type[a] (NSPS as baseline)	Tank size (10^3 liters)	Annual throughput (10^6 liters/year)	Annual turnovers
BENZENE PRODUCER							
Large facility (throughput of 224.6 x 10^6 liters/year):							
	12/9	(40/30)	ncIFR	ncIFR	980	117.1	119 (rundown tank)
	18/12	(60/39.8)	EFRps	EFRss	2,930	38.3	13
	8/5	(25/18)	cIFRps	ncIFR	240	28.7	119 (rundown tank)
	9/9	(30/30)	cIFRps	ncIFR	660	78.8	119 (rundown tank)
	13/13	(42/41.8)	ncIFR	ncIFR	1,640	21.4	13
	24/9	(80/30)	ncIFR	ncIFR	3,990	52.1	13
	27/15	(90/48)	ncIFR	ncIFR	8,630	112.8	13
Small facility (throughput of 46.3 x 10^6 liters/year):							
	3/11	(10/36)	FR	FR	80	6.5	81 (rundown tank)
	13/13	(42/41.8)	ncIFR	ncIFR	1,650	11.0	7
	8/11	(25/35.9)	ncIFR	ncIFR	490	39.8	81 (rundown tank)
	32/7	(104/24)	cIFRps	ncIFR	5,280	35.3	7
BENZENE CONSUMER (throughput of 42.1 x 10^6 liters/year):							
	12/11	(42/35.9)	ncIFR	ncIFR	1,240	11.2	9
	18/15	(60/43)	cIFRps	ncIFR	3,410	30.9	9
BULK STORAGE TERMINAL (throughput of 42.1 x 10^6 liters/year):							
	12/11	(40/35.9)	ncIFR	ncIFR	1,240	11.2	9
	18/15	(60/43)	cIFRps	ncIFR	3,410	30.9	9

[a] FR-fixed-roof tank, EFRps-external floating-roof tank with a primary seal, EFRss-external floating-roof tank with primary and secondary seals, ncIFR-noncontact internal floating-roof tank, cIFRps-contact internal floating-roof tank with primary seal.

Sections 3.2.3.1.1 and 3.2.3.2.1, the national baseline emissions from benzene storage tanks can be estimated.

3.3.3 National Baseline Emissions

To estimate the national baseline emissions from existing benzene storage tanks, it is first necessary to estimate and total the benzene emissions from the tanks in each of the existing model plants for which the fixed-roof tank CTG is the baseline. The baseline emissions from each of the existing model plants, in addition to those from each of the new model plants, are presented in Table 3-6. The emissions estimate for each existing model plant is then multiplied by the nationwide number of plants of that particular type from Table 3-4. Once this calculation is completed for each type of existing model plant, the individual estimates are summed to give the national baseline emissions. This is calculated to be about 2,200 megagrams of benzene per year. This value represents about 5 percent of the estimated 46,000 megagrams of benzene emitted from all stationary sources during 1976.[13]

Of the annual baseline emissions from benzene storage tanks, approximately 39 megagrams (2 percent) are emitted by 34 fixed-roof tanks. About 390 megagrams per year (18 percent) are emitted from 28 external floating-roof tanks. The 261 noncontact internal floating-roof tanks emit an estimated 1,400 megagrams per year, or 65 percent of the total emissions. Finally, the 171 contact internal floating-roof tanks emit the remaining 340 megagrams, or 16 percent of the total. (The numbers of fixed-roof, internal floating-roof, and external floating-roof tanks presented in this section differ from those presented in the introduction to Section 3.2 because existing fixed-roof tanks are assumed to be in compliance with the requirements of the fixed-roof tank CTG).

Table 3-6. BASELINE EMISSIONS FROM NEW AND EXISTING MODEL PLANTS

Type of plant	Existing model plant (megagrams per year)	New model plant (megagrams per year)
Large benzene producer	44	40
Small benzene producer	13	21[a]
Benzene consumer	6.5	11[a]
Bulk storage terminal	6.5	11[a]

[a] Baseline emissions from new model plants are higher than those from existing plants because new plants are assumed to comply only with the minimim requirements of the Petroleum Liquid Storage Tank New Source Performance Standard.

3.4 REFERENCES FOR CHAPTER 3

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3. U. S. Environmental Protection Agency. Control of Volatile Organic Emissions from Storage of Petroleum Liquids in Fixed-Roof Tanks. EPA-450/2-77-036. Research Triangle Park, North Carolina. December 1977.

4. U. S. Environmental Protection Agency. Control of Volatile Organic Emissions from Petroleum Liquid Storage in External Floating Roof Tanks. EPA-450/2-77-047. Research Triangle Park, North Carolina. December 1978.

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8. German Society for Petroleum Science and Carbon Chemistry (DGMK) and the Federal Ministry of the Interior (BMI). Measurement and Determination of Hydrocarbon Emissions in the Course of Storage and Transfer in Above-Ground Fixed Cover Tanks With and Without Floating Covers, BMI-DGMK Joint Projects 4590-10 and 4590-11, Translated for EPA by Literature Research Company. Annandale, Virginia.

9. U. S. Environmental Protection Agency. Measurement of Benzene Emissions from a Floating Roof Test Tank. EPA-450/3-79-020. Research Triangle Park, North Carolina. June 1979.

10. Section 114 letter survey from EPA to representatives of companies having benzene storage tanks. August 2, 1977. Requesting information regarding the storage and transfer of benzene.

11. Section 114 letter survey from EPA to representatives of companies having benzene storage tanks. December 29, 1978. Requesting information regarding types of floating roof and seals used on benzene storage tanks.

12. Section 114 letter survey from EPA to representatives of bulk storage terminals having benzene storage tanks. July 18, 1979. Requesting economic, storage, and handling information on tanks which are being and which can be used for the storage of benzene.

13. U. S. Environmental Protection Agency. Atmospheric Benzene Emissions. EPA-450/3-77-029. Research Triangle Park, North Carolina. October 1977.

4. EMISSIONS CONTROL TECHNIQUES

4.1 INTRODUCTION

As discussed in Chapter 3 of this document, there are basically three different types of benzene storage tanks: fixed-roof tanks, external floating-roof tanks, and internal floating-roof tanks.

The various techniques discussed in this chapter for controlling benzene emissions from these types of storage tanks were chosen largely on the basis of tests conducted for EPA on a 6-meter (20-foot) diameter pilot test tank fitted with several different floating roof and seal combinations. These roof and seal combinations included: (1) an external floating roof with a metallic shoe primary seal; (2) an external floating roof with a metallic shoe primary seal and a rim-mounted secondary seal; (3) a noncontact internal floating roof with shingled, vapor-mounted primary and secondary seals; (4) a contact internal floating roof with a liquid-mounted primary seal; and (5) a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal. Several roof and seal combinations which have not been tested are also discussed. Additionally, two types of vapor control systems, which have been tested during gasoline loading operations, are discussed for use with fixed-roof and internal floating-roof tanks storing benzene. Finally, prohibiting the storage of benzene in tanks is discussed as the most stringent emissions control technique.

4.2 EMISSIONS CONTROL TECHNIQUES

4.2.1 Internal Floating Roofs in Fixed-Roof Tanks

Fixed-roof tank emissions can be reduced by installing internal floating roofs and seals in the tanks to minimize evaporation of the stored product. Three floating roof and seal combinations have been tested for use in fixed-roof tanks, including (1) a noncontact internal floating roof with shingled, vapor-mounted primary and secondary seals; (2) a contact internal floating roof with a liquid-mounted primary seal; and (3) a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal. Based on the test results, a noncontact internal floating roof with shingled, vapor-mounted primary and secondary seals is less effective in reducing emissions than a contact internal floating roof with a liquid-mounted primary seal.[1] Consequently, a larger emissions reduction can be achieved by fitting a fixed-roof tank with a contact internal floating roof and a liquid-mounted primary seal rather than a noncontact internal floating roof and shingled, vapor-mounted primary and secondary seals. Installation of a continuous secondary seal on a contact internal floating roof yields an even greater emissions reduction.

Several other roof and seal combinations, which have not been tested, are also available for controlling the emissions from fixed-roof tanks. Three of these include (1) a noncontact internal floating roof with a vapor-mounted primary seal; (2) a contact internal floating roof with a vapor-mounted primary seal; and (3) a contact internal floating roof with a metallic shoe primary seal. Based on engineering judgment, a noncontact roof with a vapor-mounted primary seal would be less effective at reducing emissions than a contact roof with a vapor-mounted primary seal. In addition, based on information presented in American Petroleum Institute (API) Publication 2517[2] and on engineering judgment, a contact floating roof with a vapor-mounted primary seal would be less effective at reducing emissions than the contact roof tested, which was equipped with a liquid-mounted primary seal. Finally, based on information presented in this publication and engineering judgment, a contact floating roof with a metallic shoe primary seal would provide essentially the same degree of emissions reduction as a contact roof with a liquid-mounted primary seal.

4.2.2 Rim-Mounted Secondary Seals on External Floating Roofs

A rim-mounted secondary seal on an external floating roof is a continuous seal which extends from the floating roof to the tank wall.

covering the entire primary seal. Installed over a mechanical shoe seal, this secondary seal has been demonstrated to effectively control benzene emissions which escape from the small vapor space between the shoe and the wall, and through any openings or tears in the seal envelope (see Figure 4-1a). Rim-mounted secondary seals should also be effective in controlling emissions from the liquid- and vapor-mounted primary seals shown in Figures 4-1b, 4-1c, and 4-1d. However, their effectiveness has not be demonstrated on external floating-roof tanks so equipped storing benzene.

Another type of secondary seal, which has not been tested, is a shoe-mounted secondary seal. A shoe-mounted seal extends from the top of the shoe to the tank wall (see Figure 4-2). These seals do not provide protection against benzene leakage through the envelope. Holes, gaps, tears, or other defects in the envelope can allow direct communication between the saturated vapor under the envelope and the atmosphere; the wind can enter this space through envelope defects, flow around the circumference, and exit with saturated or nearly saturated benzene vapors.

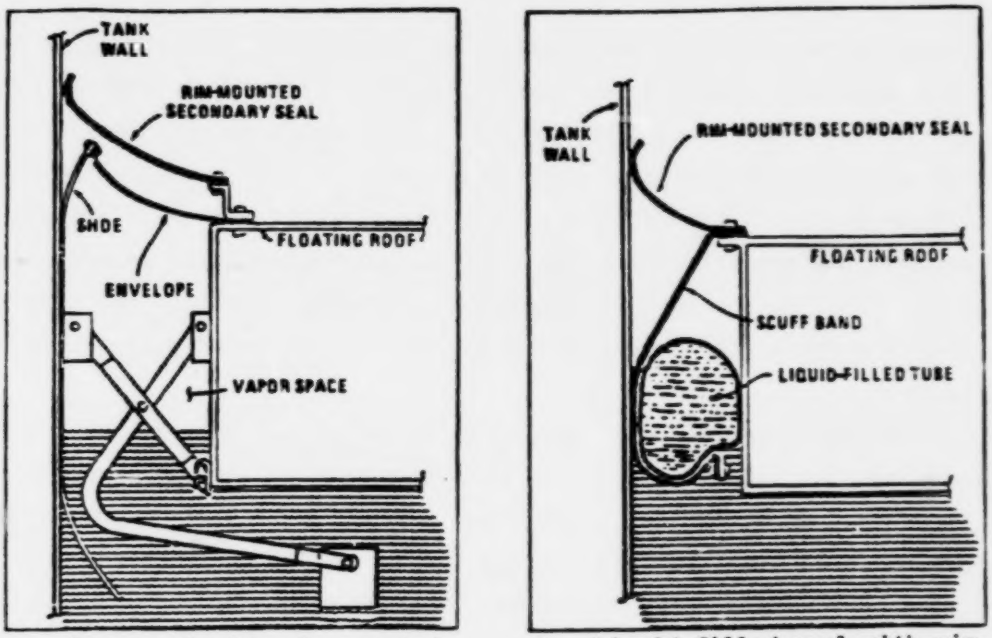
4.2.3 Fixed Roofs on External Floating-Roof Tanks

Installing a fixed roof on an existing external floating-roof tank would reduce emissions by reducing the effect of wind sweeping vapors out of the vapor space and into the atmosphere.

An alternative to the construction of a new external floating-roof tank is the construction of an internal floating-roof tank with a primary seal or both primary and secondary seals.

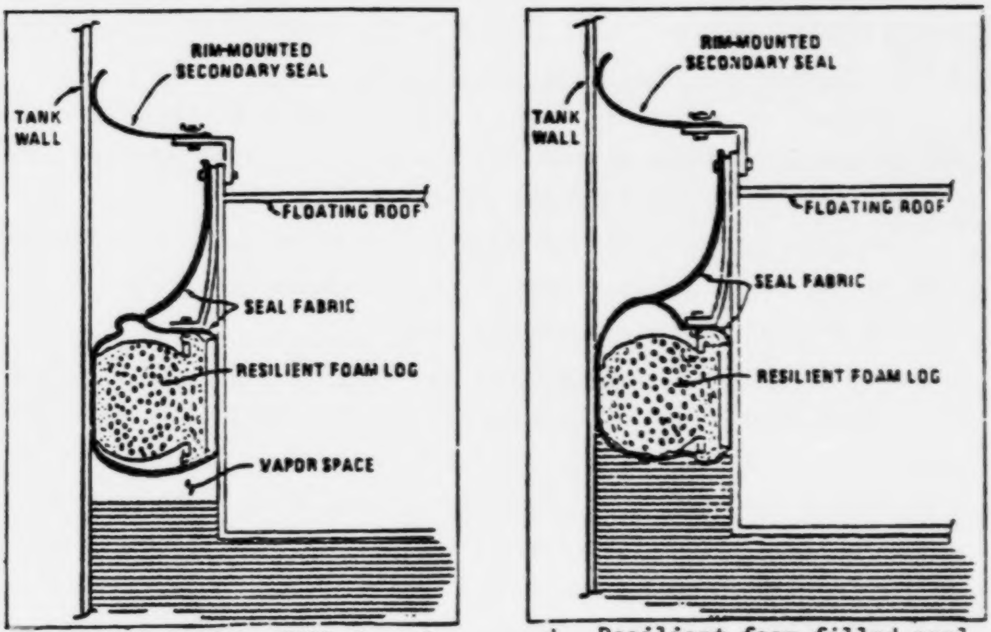
4.2.4 Rim-Mounted Secondary Seals on Noncontact Internal Floating Roofs

Because some noncontact internal floating-roof tanks have only vapor-mounted primary seals, one emissions control technique is to install rim-mounted secondary seals over the primary seals. The secondary seal, which is typically a wiper seal, minimizes the effects of air currents inside the tank sweeping vapors out of the annular vapor space. This seal, which can be either continuous or shingled, extends from the floating roof to the tank wall, covering the primary seal. Although the benefits of using a secondary seal cannot be quantified because a noncontact roof with only a vapor-mounted primary seal has not been tested, engineering


TANK WALL
RIM-MOUNTED SECONDARY SEAL
SHOE
ENVELOPE
FLOATING ROOF
VAPOR SPACE
TANK WALL
RIM-MOUNTED SECONDARY SEAL
FLOATING ROOF
SCUFF BAND
LIQUID-FILLED TUBE

a. Shoe seal with rim-mounted secondary seal.

b. Liquid-filled seal with rim-mounted secondary seal.


RIM-MOUNTED SECONDARY SEAL
TANK WALL
FLOATING ROOF
SEAL FABRIC
RESILIENT FOAM LOG
VAPOR SPACE
RIM-MOUNTED SECONDARY SEAL
TANK WALL
FLOATING ROOF
SEAL FABRIC
RESILIENT FOAM LOG

c. Resilient foam-filled seal (vapor-mounted) with rim-mounted secondary seal.

d. Resilient foam-filled seal (liquid-mounted) with rim-mounted secondary seal.

Figure 4-1(a-d). Rim-mounted secondary seals on external floating roofs.[3]

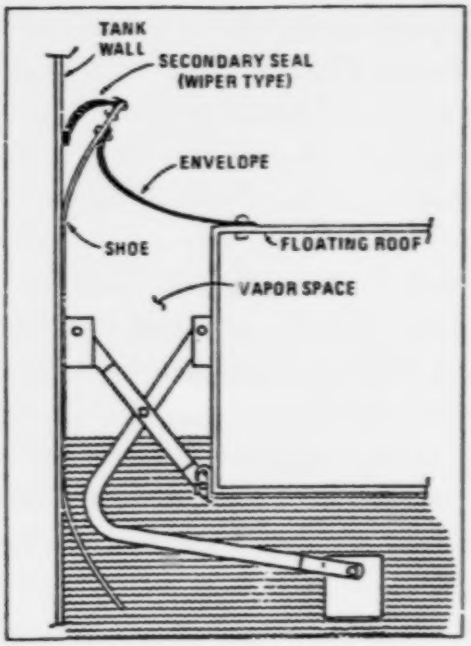

TANK WALL
SECONDARY SEAL (WIPER TYPE)
ENVELOPE
SHOE
FLOATING ROOF
VAPOR SPACE

Figure 4-2. Metallic shoe seal with shoe-mounted secondary seal.

judgment indicates that this modification would reduce the emissions from noncontact internal floating-roof tanks.

4.2.5 Contact Internal Floating Roofs in Noncontact Internal Floating-Roof Tanks

Based on the results of a recent pilot test tank study sponsored by EPA, noncontact internal floating roofs with shingled, vapor-mounted primary and secondary seals may be less effective in reducing emissions than contact internal floating roofs with liquid-mounted primary seals.[1] Consequently, one emissions control technique for internal floating-roof tanks is to use contact internal floating roofs with liquid-mounted primary seals instead of noncontact internal floating roofs with shingled, vapor-mounted primary and secondary seals. The use of a continuous secondary seal on a contact internal floating roof has been demonstrated to result in an even greater emissions reduction.

Two roof and seal combinations, which have not been demonstrated, are (1) a contact internal floating roof with a vapor-mounted primary seal, and (2) a contact internal floating roof with a metallic shoe primary seal. Information presented in API Publication 2517[2] and engineering judgment indicate that the use of either of these roof and seal combinations would result in lower emissions than the emissions associated with the use of a noncontact roof with shingled, vapor-mounted primary and secondary seals.

4.2.6 Liquid-Mounted Primary Seals on Contact Internal Floating Roofs

Based on information reported in API Publication 2517[2] and engineering judgment, vapor-mounted primary seals are less effective in reducing emissions than liquid-mounted primary seals. As a result, one technique to reduce the emissions from tanks having contact internal floating roofs is to use liquid-mounted rather than vapor-mounted primary seals.

4.2.7 Rim-Mounted Secondary Seals on Contact Internal Floating Roofs

Contact internal floating roofs, like other types of floating roofs, can have not only a primary seal to cover the annular vapor space, but also a rim-mounted secondary seal (Figure 4-3). The secondary seal, which is typically a wiper seal or a resilient foam-filled seal, minimizes the effects of the air currents inside the tank sweeping vapors out of

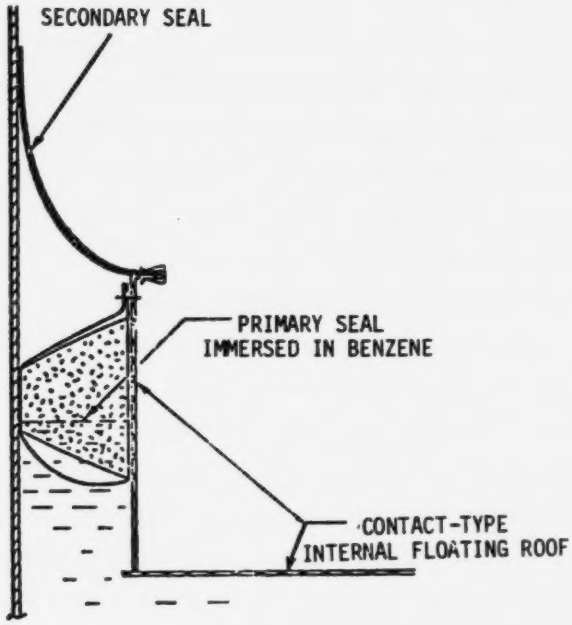

SECONDARY SEAL
PRIMARY SEAL
IMMERSED IN BENZENE
CONTACT-TYPE
INTERNAL FLOATING ROOF

Figure 4-3. Rim mounting of a secondary seal on an internal floating roof[1].

the annular vapor space. This type of seal is continuous and extends from the floating roof to the tank wall, covering the entire primary seal.

4.2.8 Vapor Control Systems on Fixed-Roof and Internal Floating-Roof Tanks

Losses can be further reduced from fixed-roof and internal floating-roof tanks by collecting the vapors and either recovering or oxidizing the benzene. This control scheme requires the addition of fixed roofs having pressure-vacuum vents to external floating-roof tanks. In a typical vapor control system, vapors remain in the tank until the internal pressure reaches a preset level. A pressure switch, which senses the pressure buildup in the tank, then activates blowers to collect and transfer the vapors. A redundant blower system is provided in this service to ensure that no vapors will be released to the atmosphere should a blower malfunction.

To prevent flashbacks from the control equipment, it is assumed that the vapors are then saturated above the upper explosive limit in a saturator. For this particular analysis, a benzene saturator (Figure 4-4) consisting of a pressure vessel, spray nozzle, heat exchanger, recycle pump, demister pad, and safety devices (water seals and a flame arrestor) is considered to be an integral component of the vapor control system. Gas blanketing of the vapor space can be used instead of saturation to prevent flashbacks; however, this method was not considered in the analysis because of the high cost involved in maintaining a continuous supply of gas on hand.

Following saturation, the vapors are introduced to a recovery or oxidation unit.

4.2.8.1 Carbon Adsorption. Carbon adsorption has not been widely used for recovering benzene vapors; however, because it has been used to recover other organic vapors, its application to benzene storage tanks should not be difficult.[4]

Carbon adsorption utilizes the principle of carbon's affinity for nonpolar hydrocarbons to remove benzene from the vapor phase. Activated carbon is the adsorbent, and the benzene vapor removed from the airstream is the adsorbate. Adsorption of the benzene vapor occurs at the surface of the adsorbent and is a physical process because no chemical change

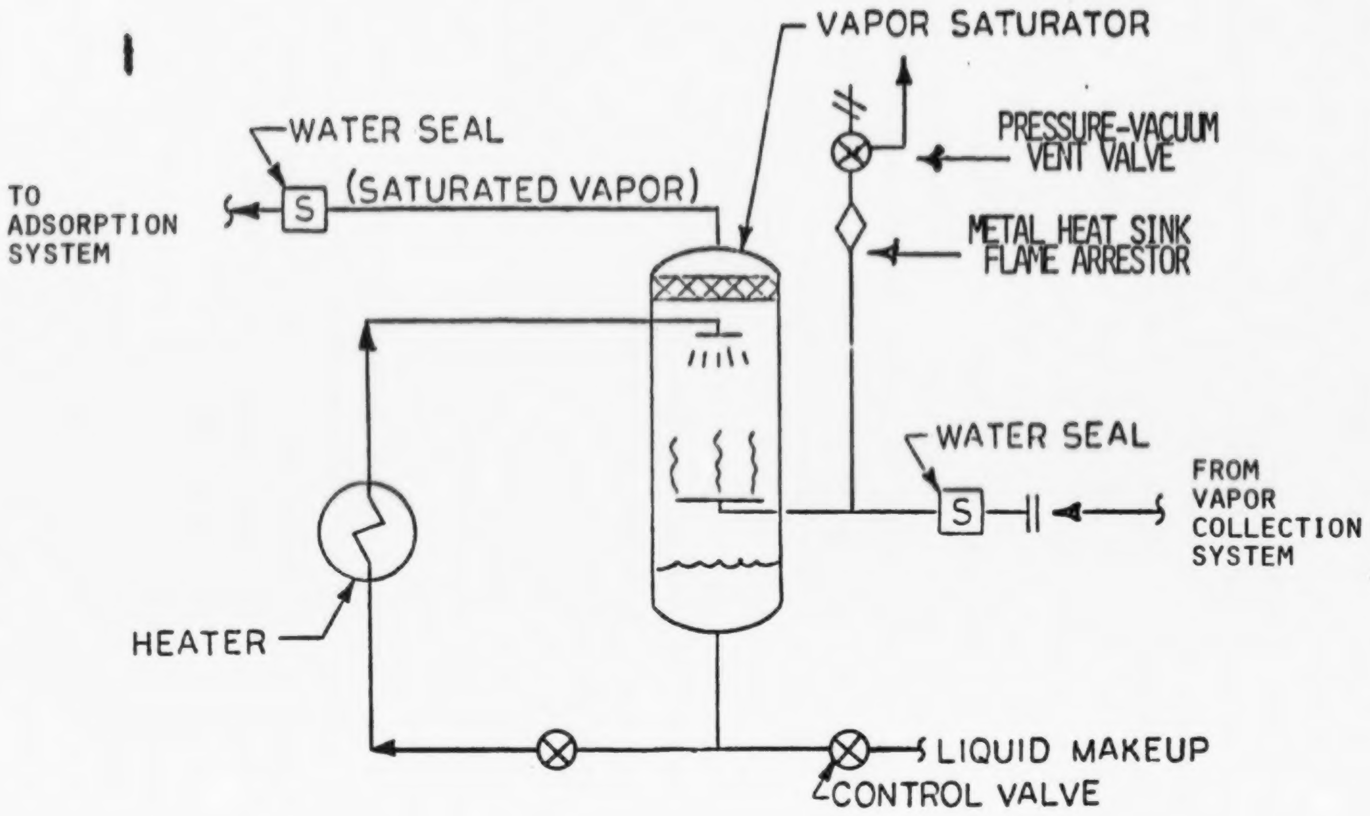

VAPOR SATURATOR
WATER SEAL
(SATURATED VAPOR)
TO
ADSORPTION
SYSTEM
S
PRESSURE-VACUUM
VENT VALVE
METAL HEAT SINK
FLAME ARRESTOR
WATER SEAL
S
FROM
VAPOR
COLLECTION
SYSTEM
HEATER
LIQUID MAKEUP
CONTROL VALVE

Figure 4-4. Benzene vapor saturator.[4]

takes place. The proposed benzene carbon adsorption unit (Figure 4-5) consists of a minimum of two carbon beds plus a regeneration system. Two or more beds are necessary to ensure that one bed will be available for use while the other is being regenerated.

Regeneration can be performed by using either steam or a vacuum. In steam regeneration, steam is circulated through the carbon bed, raising the benzene vapor pressure. The vaporized benzene is thus removed along with the steam. The steam-benzene mixture is then condensed, usually by an indirect cooling water stream, and routed to a separator. The benzene is decanted and returned to storage, and the contaminated water is sent to the plant wastewater system for disposal. Cooling water, electricity, and steam are the required utilities for a steam regeneration system. The other method of regenerating the carbon, vacuum regeneration, is performed by pulling a high vacuum on the carbon bed. The benzene vapor desorbed by this process is condensed and returned to storage.

Because the costs for both steam and vacuum regeneration are comparable and many facilities already have steam in quantities sufficient for steam regeneration, the vacuum-regenerated carbon adsorption system has been eliminated from further consideration.

4.2.8.2 Thermal Oxidation

Thermal oxidation, like carbon adsorption, has not been widely used for controlling benzene emissions. However, based on experience with other organic vapors, thermal oxidation for the incineration of benzene vapors should not be difficult.

In a typical thermal oxidation system, the air-vapor mixture is injected via a burner manifold into the combustion area of the incinerator. Pilot burners provide the ignition source and supplementally-fueled burners add heat, when required, to maintain the flame temperature between 1,030 K and 1,090 K (1,400°F and 1,500°F).

The amount of combustion air needed is regulated by temperature-controlled dampers. The concentration of benzene in the tail gas of an oxidation unit can be limited to 10 ppm.[4] Figure 4-6 shows a typical thermal oxidation unit.

It is assumed that flashback prevention and burner stability are achieved by saturating the vapors with benzene to a concentration above

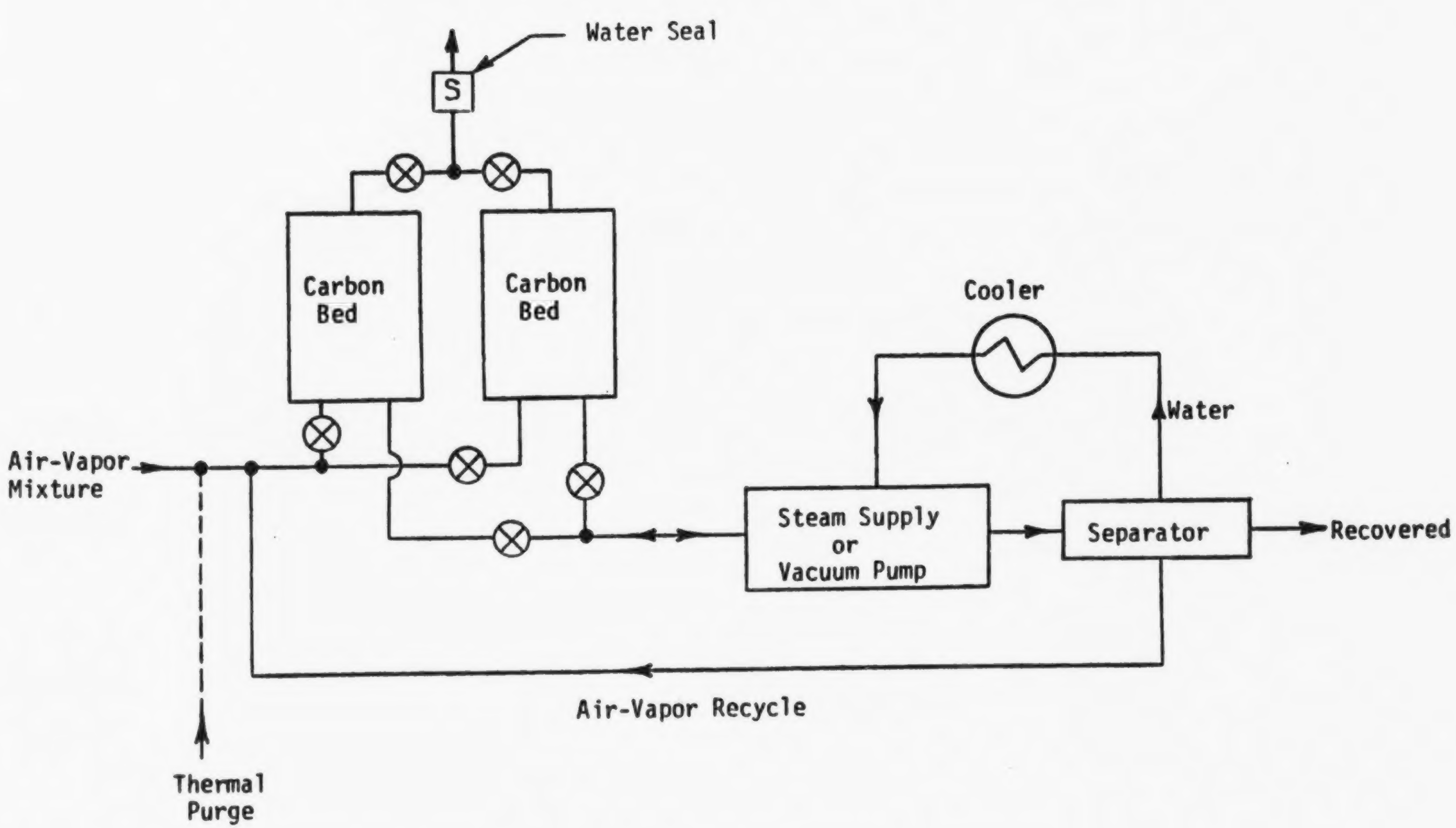

Water Seal
S
Carbon Bed
Carbon Bed
Cooler
Water
Air-Vapor Mixture
Steam Supply or Vacuum Pump
Separator
Recovered
Air-Vapor Recycle
Thermal Purge

Figure 4-5. Schematic diagram of a carbon adsorption system.

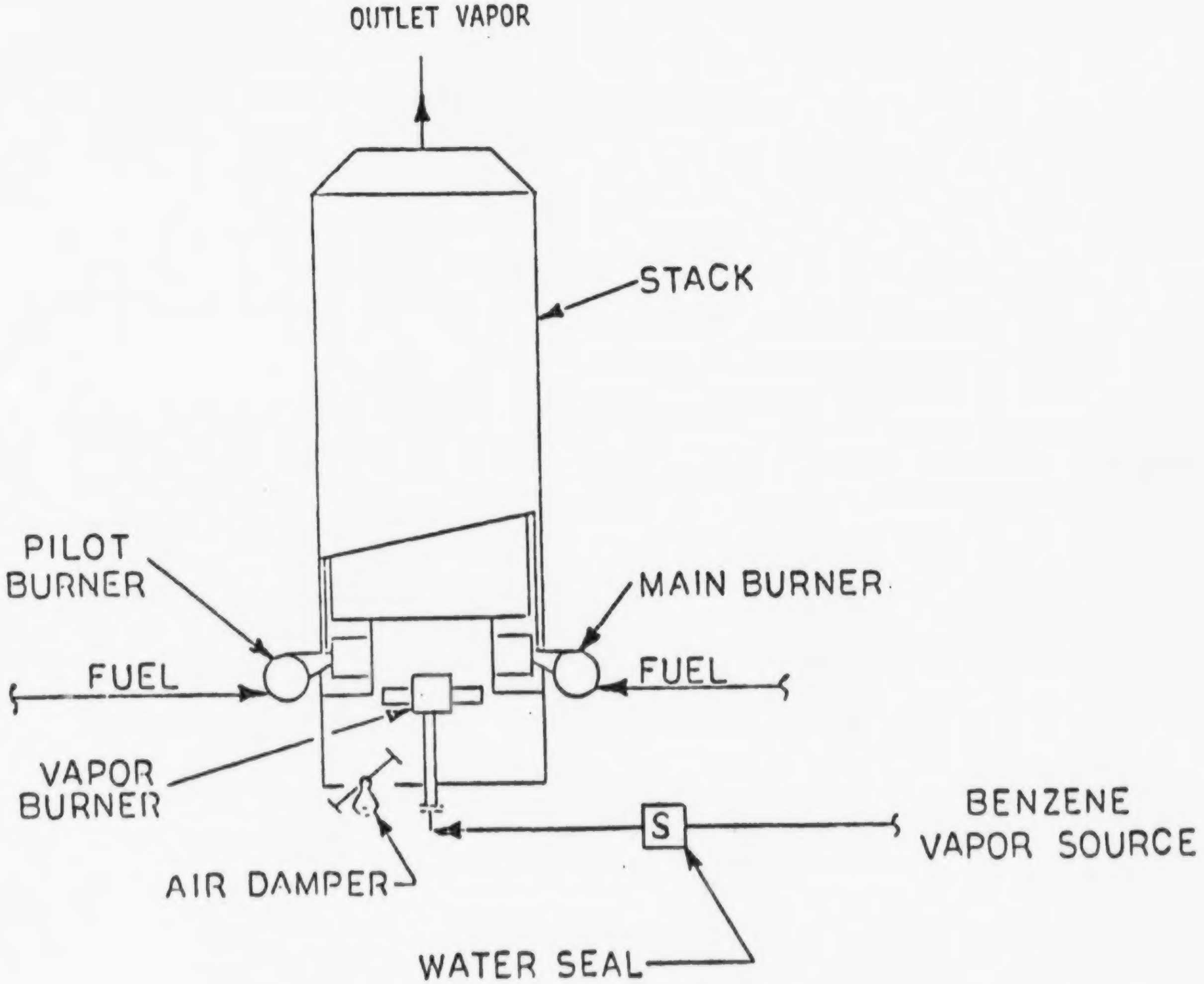

OUTLET VAPOR
STACK
PILOT BURNER
MAIN BURNER
FUEL
FUEL
VAPOR BURNER
S
BENZENE VAPOR SOURCE
AIR DAMPER
WATER SEAL

Figure 4-6. Thermal oxidation unit.[4]

the upper explosive limit. In addition, two water seal flame arrestors are used to ensure that flashbacks do not propagate from the burner to the rest of the piping system.

A significant advantage of thermal oxidation units is that they can dispose of a wide range of hydrocarbons. This could be especially important at storage facilities where numerous hydrocarbon liquids are stored which may have to be controlled in the future.

4.2.9 Prohibit the Storage of Benzene in Tanks

Prohibiting the storage of benzene in tanks is the most stringent emissions control technique being considered.

4.3 CONTROL EFFICIENCIES OF EMISSIONS CONTROL TECHNIQUES

This section establishes the typical control efficiencies expected with the use of external floating roofs with both primary and secondary seals, internal floating roofs with primary seals, internal floating roofs with both primary and secondary seals, and vapor control systems. The efficiencies are estimated for only those emissions control techniques which have been demonstrated to be effective in reducing emissions. Equations 3-1, 3-2, and 3-3, which are based on the AP-42 emissions equations for breathing and working losses and test results recently released by the Western Oil and Gas Association (WOGA), EPA, and the German Society for Petroleum Science and Carbon Chemistry (DGMK), are used to estimate fixed-roof tank emissions. Equations 3-4, 3-5, 3-6, and 3-7, which are based on the results of tests conducted for EPA, are used to estimate the emissions from (1) external floating-roof tanks with primary seals; (2) external floating-roof tanks with primary and secondary seals; (3) noncontact internal floating-roof tanks with vapor-mounted primary and secondary seals; (4) contact internal floating-roof tanks with liquid-mounted primary seals; and (5) contact internal floating-roof tanks with liquid-mounted primary seals and continuous secondary seals. Emissions from carbon adsorption and thermal oxidation vapor control systems are estimated by assuming that a saturated benzene vapor is introduced to the respective vapor control unit.

The emissions equations are based on limited amounts of empirical data and, therefore, should only be used to estimate, rather than precisely predict, the emissions. In addition, the efficiency of each emissions control technique should be used only for comparing the relative effectiveness of the control techniques.

4.3.1 Internal Floating Roofs in Fixed-Roof Tanks

If a noncontact internal floating roof with shingled, vapor-mounted primary and secondary seals is installed in a fixed-roof tank 18 meters in diameter, 12 meters in height, and undergoing 13 turnovers per year, the annual benzene emissions would be reduced from 16 megagrams to 6.5 megagrams, a 59 percent reduction. Installation of a contact internal floating roof with a liquid-mounted primary seal in the same fixed-roof tank would reduce the benzene emissions from 16 megagrams per year to 2.0 megagrams per year, an 88 percent reduction. Installing a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal in the fixed-roof tank would reduce the annual benzene emissions by 92 percent to 1.2 megagrams. Table 4-1 summarizes the control efficiencies expected with the use of each control technique.

4.3.2 Rim-Mounted Secondary Seals on External Floating Roofs

If the baseline is an 18-meter diameter, 12-meter high external floating-roof tank with 13 turnovers per year, the annual emissions would be about 14 megagrams. If this tank has a secondary seal over the primary seal, the annual emissions would be about 5.2 megagrams, a 63 percent reduction (Table 4-2).

4.3.3 Fixed Roofs on External Floating-Roof Tanks

If a fixed roof is installed on an existing external floating-roof tank 18 meters in diameter, 12 meters high, with 13 turnovers per year, the tank would have emissions on the same order of magnitude as a contact internal floating-roof tank with a liquid-mounted primary seal. As a result, the annual benzene emissions would be about 2.0 megagrams. This is an 86 percent reduction of the 14 megagrams per year emitted from the external floating-roof tank. If the same tank is retrofitted with a secondary seal in addition to the fixed roof, the annual emissions would be reduced by 91 percent to 1.2 megagrams. The efficiencies of these emissions control techniques are summarized in Table 4-2.

If a new external floating-roof tank with primary and secondary seals is the baseline, the construction instead of a contact internal

Table 4-1. EFFICIENCIES OF EMISSIONS CONTROL TECHNIQUES FOR FIXED-ROOF TANKS[a]

Emissions control technique[b]	Annual benzene emissions (megagrams per year)	Percent emissions reduction from baseline
ncIFRss	6.5	59
cIFRps	2.0	88
cIFRss	1.2	92
Vapor control system		
Carbon adsorption	0.89	94
Thermal oxidation	0.67	96

[a] Baseline: fixed-roof tank, tank dimensions - 18 m-diameter x 12 m-height, tank capacity-2,930,000 liters, annual turnovers - 13, and annual emissions - 16 megagrams.

[b] ncIFRss - noncontact internal floating roof with vapor-mounted primary and secondary seals, cIFRps - contact internal floating roof with a liquid-mounted primary seal, cIFRss - contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.

Table 4-2. EFFICIENCIES OF EMISSIONS CONTROL TECHNIQUES FOR EXTERNAL FLOATING-ROOF TANKS WITH PRIMARY SEALS[a]

Emissions control technique[b]	Annual benzene emissions (megagrams per year)	Percent emissions reduction from baseline
EFRss	5.2	63
ncIFRss	6.5	54
cIFRps	2.0	86
cIFRss	1.2	91
Vapor control system		
Carbon adsorption	0.89	94
Thermal oxidation	0.67	95

[a] Baseline: external floating-roof tank with a primary seal, tank dimensions - 18-m diameter x 12-m height, tank capacity - 2,930,000 liters, annual turnovers - 13, and annual emissions - 14 megagrams.

[b] EFRss - external floating roof with a secondary seal, ncIFRss - noncontact internal floating roof with vapor-mounted primary and secondary seals, cIFRps - contact internal floating roof with a liquid-mounted primary seal, cIFRss - contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.

floating-roof tank with a liquid-mounted primary seal would reduce annual emissions to 2.0 megagrams. This is a 62 percent reduction from the baseline emissions of 5.2 megagrams per year. A 77 percent reduction, resulting in annual emissions of 1.2 megagrams, would be achieved with construction of a contact internal floating-roof tank with primary and secondary seals (Table 4-3).

Another alternative to the construction of a new external floating-roof tank is to construct a noncontact internal floating-roof tank. Using an external floating-roof tank with a primary seal as the baseline, this alternative would result in a 54 percent reduction of the annual emissions from 14 to 6.5 megagrams (Table 4-2). If a new external floating-roof tank with primary and secondary seals is the baseline, the annual emissions may increase with the use of a noncontact internal floating-roof tank (Table 4-3).

4.3.4 Contact Internal Floating Roofs in Noncontact Internal Floating-Roof Tanks

Installing a contact internal floating roof with a liquid-mounted primary seal in a noncontact internal floating-roof tank 18 meters in diameter, 12 meters high, and undergoing 13 turnovers per year, would reduce the annual benzene emissions to 2.0 megagrams. This is a 69 percent reduction from the 6.5 megagrams per year emitted from the noncontact internal floating-roof tank (Table 4-4).

If a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal is installed in a noncontact internal floating-roof tank, the annual emissions would be reduced by 82 percent to 1.2 megagrams (Table 4-4).

4.3.5 Rim-Mounted Secondary Seals on Contact Internal Floating Roofs

Installation of a secondary seal on an 18-meter diameter, 12-meter high, contact internal floating-roof tank with 13 turnovers per year would reduce the annual benzene emissions from 2.0 megagrams to 1.2 megagrams. This is a 40 percent reduction in emissions (Table 4-5).

4.3.6 Vapor Control Systems on Fixed-Roof and Internal Floating-Roof Tanks

A benzene saturator is assumed to be an integral component of both the carbon adsorption and thermal oxidation vapor control systems. The purpose of the benzene saturator is to raise the benzene concentration of

Table 4-3. EFFICIENCIES OF EMISSIONS CONTROL TECHNIQUES FOR EXTERNAL FLOATING-ROOF TANKS WITH PRIMARY AND SECONDARY SEALS[a]

Emissions control technique[b]	Annual benzene emissions (megagrams per year)	Percent emissions reduction from baseline[c]
ncIFRss	6.5	(25)
cIFRps	2.0	62
cIFRss	1.2	77
Vapor control system		
Carbon adsorption	0.89	83
Thermal oxidation	0.67	87

[a] Baseline: external floating-roof tank with primary and secondary seals, tank dimensions - 18-m diameter x 12-m height, tank capacity - 2,930,000 liters, annual turnovers - 13, and annual emissions - 5.2 megagrams.

[b] ncIFRss - non-contact internal floating roof with vapor-mounted primary and secondary seals, cIFRps - contact internal floating roof with liquid-mounted primary seal, cIFRss - contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.

[c] Percent emissions increase is indicated in parenthesis.

Table 4-4. EFFICIENCIES OF EMISSIONS CONTROL TECHNIQUES FOR NONCONTACT INTERNAL FLOATING-ROOF TANKS WITH VAPOR-MOUNTED PRIMARY AND SECONDARY SEALS[a]

Emissions control technique[b]	Annual benzene emissions (megagrams per year)	Percent emissions reduction from baseline
cIFRps	2.0	69
cIFRss	1.2	82
Vapor control system		
Carbon adsorption	0.89	86
Thermal oxidation	0.67	90

[a] Baseline: noncontact internal floating-roof tank with vapor-mounted primary and secondary seals, tank dimensions - 18-m diameter x 12-m height, tank capacity - 2,930,000 liters, annual turnovers - 13, and annual emissions - 6.5 megagrams.

[b] cIFRps - contact internal floating roof with a liquid-mounted primary seal, cIFRss - contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.

Table 4-5. EFFICIENCIES OF EMISSIONS CONTROL TECHNIQUES FOR CONTACT INTERNAL FLOATING-ROOF TANKS WITH LIQUID-MOUNTED PRIMARY SEALS[a]

Emissions control technique[b]	Annual benzene emissions (megagrams per year)	Percent emissions reduction from baseline
cIFRss	1.2	40
Vapor control system		
Carbon adsorption	0.89	56
Thermal oxidation	0.67	66

[a] Baseline: contact internal floating-roof with a liquid-mounted primary seal, tank dimensions - 18-m diameter x 12-m height, tank capacity - 2,930,000 liters, annual turnovers - 13, and annual emissions - 2.0 megagrams.

[b] cIFRss - contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.

the collected vapor above the upper explosive limit and, thus, help ensure the safe operation of the system. The efficiency of a carbon adsorption or thermal oxidation unit is directly related to the benzene concentration of the gas stream leaving the saturator and not the concentration of the gas stream leaving the storage tank.

4.3.6.1 Carbon Adsorption. It is estimated that a carbon adsorption vapor control system would reduce the emissions from an in-line benzene saturator by approximately 96 percent. This efficiency is based on an estimated carbon adsorption unit efficiency of 98 percent during gasoline loading operations[5] and an assumed collection efficiency of 98 percent of the emissions from the benzene saturator.

If a carbon adsorption system with this efficiency is used on a 18-meter diameter, 12-meter high fixed-roof tank undergoing 13 turnovers per year, the benzene emissions would be reduced from 16 megagrams per year to 0.89 megagram per year, a 94 percent reduction (Table 4-1).

Because the emissions from the carbon adsorption unit are directly related to the volume of saturated vapor entering the unit, the use of an internal floating roof in the same fixed-roof tank would not reduce the overall emissions. Consequently, the emissions from a carbon adsorption unit which is fitted to a noncontact or a contact internal floating-roof tank would remain unchanged at 0.89 megagram per year. However, because the annual emissions from these two types of internal floating-roof tanks are only 6.5 megagrams and 2.0 megagrams, respectively, the emissions reduction efficiencies using a carbon adsorption system are only 86 and 56 percent, respectively (Tables 4-4 and 4-5). These efficiencies are lower than the 96 percent efficiency expected because the vapor emitted from each tank is saturated with benzene for safety reasons before its introduction to the carbon adsorption unit. Consequently, the emissions reductions achieved by the carbon adsorber are based on the benzene concentration leaving the saturator and not the concentration from the storage tank.

In order to use a carbon adsorption system on an external floating-roof tank, a fixed roof with pressure-vacuum vents must be installed over the floating roof. The emissions from carbon adsorption systems used on modified external floating-roof tanks are shown in Tables 4-2 and 4-3.

4.3.6.2 Thermal Oxidation. A thermal oxidation vapor control system will reduce the emissions from an in-line benzene saturator by approximately 97 percent. This efficiency is based on a measured thermal oxidation unit efficiency of 99 percent during gasoline loading operations[5] and an assumed 98 percent collection efficiency of the emissions from the saturator.

Connecting a thermal oxidation system of 97 percent efficiency to a fixed-roof tank 18 meters in diameter, 12 meters high, and undergoing 13 turnovers per year, would reduce the benzene emissions from 16 megagrams per year to about 0.67 megagram per year, a 96 percent reduction (Table 4-1).

If a thermal oxidation system is used on a noncontact internal floating-roof tank, the emissions would be reduced from 6.5 megagrams per year to 0.67 megagram per year, a 90 percent reduction (Table 4-4). Similar to carbon adsorption, the percent emissions reduction can be less than the overall control efficiency indicated, because vapor from the storage tank is saturated prior to being introduced to the thermal oxidation unit.

The use of this system on a contact internal floating-roof tank would reduce the emissions from 2.0 megagrams per year to 0.67 megagram per year, a 66 percent reduction (Table 4-5).

Before a thermal oxidation system can be used on an external floating-roof tank, the tank must be modified by installing a fixed roof with pressure-vacuum vents over the floating roof. The emissions from thermal oxidation systems used on modified external floating-roof tanks are shown in Tables 4-2 and 4-3.

4.3.7 Prohibit the Storage of Benzene in Tanks

Prohibiting the storage of benzene in tanks is a technique for eliminating all benzene emissions from these sources.

4.4 RETROFIT PROBLEMS

This section discusses possible problems fixed-roof tank owners and operators may have in retrofitting their tanks with internal floating roofs. In addition, problems associated with the retrofitting of rim-mounted secondary seals on external floating roofs, conversion of external floating-roof tanks to internal floating-roof tanks, and the retrofitting of vapor control systems to tanks will be discussed.

4.4.1 Internal Floating Roofs in Fixed-Roof Tanks

Several modifications to a fixed-roof tank may be necessary before it can be equipped with an internal floating roof. Tank wall deformations and obstructions may require correction, and special structural modifications such as bracing, reinforcing, and plumbing vertical columns may be necessary. Antirotational guides should be installed to keep cover openings in alignment with roof openings. Special vents must be installed on the fixed roof or on the walls at the top of the tank to minimize the possibility of benzene vapors approaching the flammable range in the vapor space.

4.4.2 Rim-Mounted Secondary Seals on External Floating Roofs

Retrofitting problems may be encountered when a secondary seal is installed above a primary seal that can accommodate a large amount of gap. Some secondary seals may be unable to span as large a gap and, consequently, excessive gaps may result between the secondary seal and the tank wall.

4.4.3 Fixed Roofs On External Floating-Roof Tanks

In order to install a fixed roof on an existing external floating-roof tank, several tank modifications may be required. For example, special structural modifications such as bracing and reinforcing may be necessary to permit the external floating-roof tank to accommodate the added weight of a fixed roof. Vertical columns may be required to support the fixed roof and, as a result, modifications to the floating roof will be necessary to accommodate these columns. In addition, antirotational guides should be installed to keep cover openings in alignment with roof openings.

4.4.4 Vapor Control Systems on Existing Benzene Storage Tanks

Some problems may be encountered in siting a carbon adsorption or thermal oxidation unit close to benzene tanks because of spacing constraints. In addition, cold climates may necessitate the use of insulation on exposed vapor collection lines to prevent freezing of the benzene vapors. Electricity will also be required to operate a vapor collection system.

4.4.4.1 Carbon Adsorption. If a carbon adsorption system is employed for reducing emissions, steam can be used for regenerating the carbon beds. However, a source of steam may not be readily available at some facilities. In addition, water for cooling may also be in short supply. Furthermore, even if cooling water is available, disposal of benzene-contaminated condensate could be a problem.

If water for cooling is not easily obtained or if steam is not readily available, a vacuum regeneration system with a closed loop freon refrigeration unit can be used to regenerate the carbon. This method would eliminate the problem of disposing of benzene-contaminated water.

4.4.4.2 Thermal Oxidation. The biggest problem with the use of thermal oxidation is the requirement for supplemental fuel to maintain the flame temperature. Some facilities may not have adequate fuel supplies readily available.

4.5 CONTROL OF EMISSIONS DURING STARTUP, SHUTDOWN, UPSETS, AND BREAKDOWNS

Benzene emissions from storage tanks having floating roofs and seals as the emissions control equipment are extremely difficult to quantify because of the varying loss mechanisms and the number of variables affecting loss rate. To help ensure that some degree of emissions control is achieved during the initial filling (startup) of a tank and to minimize the likelihood of operational failures (upsets and breakdowns) of the control equipment, regular inspections of the control equipment should be required. These inspections will help ensure that the control equipment is being properly operated and maintained. The emissions resulting from cleaning and degassing (shutdown) operations would not be reduced by the control equipment.

If emissions control is provided by a vapor control system, the emissions during initial filling operations and cleaning and degassing operations would be collected and transferred by blowers to a recovery or oxidation unit. When upsets or breakdowns of the blowers occur, a redundant blower system would be used to transfer the vapors to the control unit. Should a carbon adsorption unit become inoperative, another carbon bed must be available to provide continuous emissions control.

4.6 REFERENCES FOR CHAPTER 4

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4. U.S. Environmental Protection Agency. Evaluation of Control Technology for Benzene Transfer Operations. Publication No. EPA-450/3-78-018. Research Triangle Park, North Carolina. April 1978.

5. Letter from McLaughlin, Nancy D., U.S. Environmental Protection Agency to David Ailor, TRW. May 3, 1979. Comments on the benzene storage model plants package.

5. REGULATORY ALTERNATIVES

5.1 INTRODUCTION

This chapter presents the regulatory alternatives being considered for controlling benzene emissions from fixed-roof, external floating-roof, and internal floating-roof storage tanks. In addition, the rationale used in the development of these alternatives is presented.

5.2 DEVELOPMENT OF REGULATORY ALTERNATIVES

In order to develop a set of regulatory alternatives for consideration, control options were first selected for application to new and existing benzene storage tanks, respectively. Each control option for existing tanks was then combined with a control option for new tanks to form a regulatory alternative applicable to both new and existing tanks.

5.2.1 Selection of Control Options

The control options selected for reducing benzene emissions from benzene storage tanks were developed by applying the various emissions control techniques discussed in Chapter 4 to the three types of tanks discussed in Chapter 3. The control options for existing and for new benzene storage tanks are presented in Tables 5-1 and 5-2, respectively.

The fixed-roof tank, which generally has the largest emissions of any of the three types of tanks, is the only type of tank affected by Control Option I for existing tanks. This option, which is identical to Option I for new tanks, would require that each fixed-roof tank have either a noncontact or a contact internal floating roof. Each new or existing fixed-roof tank which has a capacity greater than 150,000 liters and which is located in an ozone nonattainment area is already required to have an internal floating roof by the fixed-roof tank Control Techniques Guideline (CTG).

Table 5-1. CONTROL OPTIONS FOR EXISTING BENZENE STORAGE TANKS
(Fixed-Roof Tank CTG as Baseline)

- Option 0 - Baseline (no additional standard)
- Option I - Each fixed-roof storage tank must be retrofitted with an internal floating roof (contact or noncontact).
- Option II - Each fixed-roof storage tank must be retrofitted with an internal floating roof (contact or non-contact); each external floating-roof storage tank must be retrofitted with a secondary seal.
- Option III - Each fixed-roof, external floating-roof, and internal floating-roof storage tank must be converted to a contact internal floating-roof storage tank with a liquid-mounted primary seal.
- Option IV - Each fixed-roof, external floating-roof, and internal floating-roof storage tank must be converted to a contact internal floating-roof storage tank with a liquid-mounted primary seal and a continuous secondary seal.
- Option V - Each fixed-roof, external floating-roof, and internal floating-roof storage tank must be fitted to a vapor control system. Two vapor control systems which have been analyzed in detail include:

  A. Steam-regenerated carbon adsorption system.

  B. Thermal oxidation system.
- Option VI - Prohibit the storage of benzene in tanks.

Table 5-2. CONTROL OPTIONS FOR NEW BENZENE STORAGE TANKS
(Petroleum Liquid Storage Tank NSPS as Baseline)

- Option 0 - Baseline (no additional standard).
- Option I - Each fixed-roof storage tank must have an internal floating roof (contact or non-contact).
- Option II - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal.
- Option III - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.
- Option IV - Each storage tank must be fitted to a vapor control system. Two vapor control systems which have been analyzed in detail include:
    A. Steam-regenerated carbon adsorption system.
    B. Thermal oxidation system.
- Option V - Prohibit the storage of benzene in tanks.

The external floating-roof tank, which is the second largest source of emissions, and the fixed-roof tank are both affected by Control Option II for existing tanks. Each existing external floating-roof tank would be required to have both primary and secondary seals. In addition, each existing fixed-roof tank would be required to have an internal floating roof as prescribed in Option I. No such option applies to new tanks because new external floating-roof tanks are already required to have primary and secondary seals by the Petroleum Liquid Storage Tank New Source Performance Standard (NSPS) promulgated on April 4, 1980.

At this point in the development of the control options, both fixed-roof and external floating-roof tanks have been controlled. The third largest source of emissions is the noncontact internal floating-roof tank. As a result, the next control options for new and existing tanks (Options II and III, respectively) would require that each tank have a fixed roof and a contact internal floating roof with a liquid-mounted primary seal.

Contact internal floating roofs with liquid-mounted primary seals and continuous secondary seals are required in the next control options (Options III and IV for new and for existing tanks, respectively) to further reduce the benzene emissions from internal floating-roof tanks.

Options IV and V for new and existing tanks, respectively, would require the use of vapor control systems, such as carbon adsorption or thermal oxidation. Option V would make it necessary to retrofit existing external floating-roof tanks with fixed roofs and pressure-vacuum valves to accommodate the vapor collection systems.

The last control options (Options V and VI for new and for existing tanks, respectively) would prohibit the storage of benzene in tanks. Tables 5-3 and 5-4 summarize the impacts that each control option for existing and new tanks, respectively, would have on each type of storage tank.

5.2.1.1 Estimated Benzene Emissions From New and Existing Model Plants. The estimated benzene emissions for each of the control options as applied to the existing and new model plants shown in Table 5-5 are presented in Tables 5-6 and 5-7, respectively. The baseline emissions level (Option 0),

Table 5-3. IMPACTS OF EACH CONTROL OPTION ON EXISTING BENZENE STORAGE TANKS[a]

Existing storage tank	Control option I	II	III	IV	V
FR	IFRps	IFRps	cIFRps	cIFRps	Vapor control system
EFRps	---	EFRss	cIFRps[b]	cIFRss[b]	A. Carbon adsorption[b]
ncIFR	---	---	cIFRps[c]	cIFRss	B. Thermal oxidation[b]
cIFRps	---	---	---	cIFRss	

[a] FR - fixed-roof tank, EFRps - external floating-roof tank with a primary seal, EFRss - external floating-roof tank with primary and secondary seals, ncIFR - noncontact internal floating-roof tank, cIFRps - contact internal floating-roof tank with a liquid-mounted primary seal, cIFRss - contact internal floating-roof tank with a liquid-mounted primary seal and continuous secondary seal.

[b] Requires addition of fixed roof to external floating-roof tank.

[c] Requires replacement of or equivalency determination for noncontact internal floating roof.

Table 5-4. IMPACTS OF EACH CONTROL OPTION ON NEW BENZENE STORAGE TANKS[a]

New storage tank	Control option			
	I	II	III	IV
FR	IFRps	cIFRps	cIFRss	
EFRss	---	cIFRps	cIFRss	Vapor control system
ncIFR	---	cIFRps	cIFRss	A. Carbon adsorption B. Thermal oxidation
cIFRps	---	---	cIFRss	

[a] FR - fixed-roof tank, EFRss - external floating-roof tank with primary and secondary seals, ncIFR - noncontact internal floating-roof tank, cIFRps - contact internal floating-roof tank with liquid-mounted primary seal, cIFRss - contact internal floating-roof tank with liquid-mounted primary seal and continuous secondary seal.

Table 5-5. MODEL BENZENE STORAGE PLANTS

Type of model plant	Tank dimensions (diameter/height) (meters)	(feet)	Existing tank type[a] (CTG as baseline)	New tank type[a] (NSPS as baseline)	Tank size (10^3 liters)	Annual throughput (10^6 liters/year)	Annual turnovers
BENZENE PRODUCER							
Large facility (throughput of 224.6 x 10^6 liters/year):							
	12/9	(40/30)	ncIFR	ncIFR	980	117.1	119 (rundown tank)
	18/12	(60/39.8)	EFRps	EFRss	2,930	38.3	13
	8/5	(25/18)	cIFRps	ncIFR	240	28.7	119 (rundown tank)
	9/9	(30/30)	cIFRps	ncIFR	660	78.8	119 (rundown tank)
	13/13	(42/41.8)	ncIFR	ncIFR	1,640	21.4	13
	24/9	(80/30)	ncIFR	ncIFR	3,990	52.1	13
	27/15	(90/48)	ncIFR	ncIFR	8,630	112.8	13
Small facility (throughput of 46.3 x 10^6 liters/year):							
	3/11	(10/36)	FR	FR	80	6.5	81 (rundown tank)
	13/13	(42/41.8)	ncIFR	ncIFR	1,650	11.0	7
	8/11	(25/35.9)	ncIFR	ncIFR	490	39.8	81 (rundown tank)
	32/7	(104/24)	cIFRps	ncIFR	5,280	35.3	7
BENZENE CONSUMER (throughput of 42.1 x 10^6 liters/year):							
	12/11	(40/35.9)	ncIFR	ncIFR	1,240	11.2	9
	18/15	(60/48)	cIFRps	ncIFR	3,410	30.9	9
BULK STORAGE TERMINAL (throughput of 42.1 x 10^6 liters/year):							
	12/11	(40/35.9)	ncIFR	ncIFR	1,240	11.2	9
	18/15	(60/43)	cIFRps	ncIFR	3,410	30.9	9

---

[a] FR-fixed-roof tank, EFRps-external floating-roof tank with a primary seal, EFRss-external floating-roof tank with primary and secondary seals, ncIFR-noncontact internal floating-roof tank, cIFRps-contact internal floating-roof tank with primary seal.

Table 5-6. EMISSIONS FOR CONTROL OPTIONS - EXISTING MODEL PLANTS
(Fixed-roof Tank CTG as Baseline)

Control option	Large producer (megagrams per year)	Small producer (megagrams per year)	Consumer (megagrams per year)	Bulk storage terminal (megagrams per year)
0 (Baseline)[a]	44	13	6.5	6.5
I	44	12 - 13[b]	6.5	6.5
II	36	12 - 13[b]	6.5	6.5
III	13	6.3	3.3	3.3
IV	7.7	3.9	2.0	2.0
V(A)[c]	9.1	2.2	1.1	1.1
V(B)[d]	6.8	1.7	0.83	0.83
VI	0	0	0	0

[a] No additional standard.

[b] Range of emissions for control option which allows the use of contact and noncontact internal floating roofs, respectively, in affected tanks.

[c] Steam-regenerated carbon adsorption system.

[d] Thermal oxidation system.

Table 5-7. EMISSIONS FOR CONTROL OPTIONS - NEW MODEL PLANTS
(Petroleum Liquid Storage Tank NSPS as Baseline)

Control option	Large producer (megagrams per year)	Small producer (megagrams per year)	Consumer (megagrams per year)	Bulk storage terminal (megagrams per year)
0 (Baseline)[a, b]	40	21	11	11
I	40	20 - 21[c]	11	11
II	13	6.3	3.3	3.3
III	7.7	3.9	2.0	2.0
IV(A)[d]	9.1	2.2	1.1	1.1
IV(B)[e]	6.8	1.7	0.83	0.83
V	0	0	0	0

[a] No additional standard.

[b] Baseline emissions from new model facilities are higher than those from existing facilities because new facilities are assumed to only comply with the minimum requirements of the Petroleum Liquid Storage Tank NSPS.

[c] Range of emissions for control option which allows the use of contact and noncontact internal floating roofs, respectively, in affected tanks.

[d] Steam-regenerated carbon adsorption system.

[e] Thermal oxidation system.

which represents the level of emissions control achieved by an affected facility in the absence of additional EPA standards, can be used as a basis for comparing the performance of the various control options. The selection of the baseline and the development of the model plants are discussed in Chapter 3.

5.2.2 Regulatory Alternatives

The possibility exists that different control options might be applied to new and existing tanks because of the higher costs and economic impacts associated with the retrofitting of existing tanks. In order to evaluate the impacts of applying different control options to new and existing tanks, the control options listed in Table 5-1 for existing tanks were combined with the control options listed in Table 5-2 for new tanks to produce the matrix of regulatory alternatives in Table 5-8.

Upon analysis, some of the alternatives have been eliminated from consideration in view of their unreasonableness. Regulatory Alternatives I-0, II-0, III-0, IV-0, V(A)-0, V(B)-0, II-I, III-I, IV-I, V(A)-I, V(B)-I, IV-II, V(A)-II, V(B)-II, V(A)-III, and V(B)-III have been eliminated because these alternatives have more stringent requirements for existing tanks than for new tanks. This was considered unreasonable because annualized cost and cost effectiveness data generally indicate that compliance with a control option is cheaper for new tanks than for existing tanks, because no retrofit costs are involved.

In addition, Alternatives VI-0, VI-I, VI-II, VI-III, VI-IV(A), VI-IV(B), VI-V, 0-V, I-V, II-V, III-V, IV-V, V(A)-V, and V(B)-V, which would prohibit the storage of benzene in tanks, have also been eliminated from consideration. Prohibiting the storage of benzene in tanks would mean that benzene production and consumption would have to be coordinated so that all benzene would be used immediately after production. Such coordination between production and consumption would be very difficult to achieve in practice, especially where the production and consumption facilities are remote from each other. To avoid these problems, it is likely that an owner or operator of a process requiring benzene as a feedstock would use an alternate feedstock. However, the question of alternate feedstocks for benzene is more appropriately examined in

Table 5-8. MATRIX OF REGULATORY ALTERNATIVES[a]

Control options for existing tanks	Control options for new tanks						
	0	I	II	III	IV(A)	IV(B)	V
0	0-0	0-I	0-II	0-III	0-IV(A)	0-IV(B)	X
I	X	I-I	I-II	I-III	I-IV(A)	I-IV(B)	X
II	X	X	II-II	II-III	II-IV(A)	II-IV(B)	X
III	X	X	III-II	III-III	III-IV(A)	III-IV(B)	X
IV	X	X	X	IV-III	IV-IV(A)	IV-IV(B)	X
V(A)	X	X	X	X	V(A)-IV(A)	V(A)-IV(B)	X
V(B)	X	X	X	X	V(B)-IV(A)	V(B)-IV(B)	X
VI	X	X	X	X	X	X	X

[a] Regulatory alternatives marked with an "X" have been eliminated from further consideration (see Section 5.2.2).

regulatory packages for petroleum refineries and specific chemical manufacturing processes. Consequently, alternatives which prohibit the storage of benzene in either new or existing storage tanks are not evaluated in the remainder of this document.

The regulatory alternatives which are being evaluated are summarized in Table 5-9.

Table 5-9. SUMMARY OF REGULATORY ALTERNATIVES

0- EXISTING: Option 0: Baseline (no additional standard) - Fixed-roof tank CTG, which recommends that each fixed-roof tank with a capacity greater than 150,000 liters have an internal floating roof (assumed to be noncontact).

- 0 NEW: Option 0: Baseline (no additional standard) - Petroleum Liquid Storage Tank NSPS, which requires that each tank constructed after May 18, 1978, which has a capacity greater than about 150,000 liters have either (1) an external floating roof with primary and secondary seals, or (2) a fixed roof and an internal floating roof (assumed to be noncontact).
- I Option I - Each fixed-roof storage tank must have an internal floating roof (contact or noncontact).
- II Option II - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal.
- III Option III - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.
- IV(A) Option A - Each storage tank must be fitted to a steam-regenerated carbon adsorption system.
- IV(B) Option B - Each storage tank must be fitted to a thermal oxidation system.

I- EXISTING: Option I - Each fixed-roof storage tank must be retrofitted with an internal floating roof (contact or noncontact).

- I NEW: Option I - Each fixed-roof storage tank must have an internal floating roof (contact or noncontact).
- II Option II - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal.
- III Option III - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.
- IV(A) Option A - Each storage tank must be fitted to a steam-regenerated carbon adsorption system.
- IV(B) Option B - Each storage tank must be fitted to a thermal oxidation system.

(continued)

Table 5-9. Continued

II-		EXISTING: Option II - Each fixed-roof storage tank must be retrofitted with an internal floating roof (contact or noncontact); each external floating-roof storage tank must be retrofitted with a secondary seal.
	II	NEW: Option II - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal.
	III	Option III - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.
	IV(A)	Option A - Each storage tank must be fitted to a steam-regenerated carbon adsorption system.
	IV(B)	Option B - Each storage tank must be fitted to a thermal oxidation system.
III-		EXISTING: Option III - Each fixed-roof, external floating-roof, and internal floating-roof storage tank must be converted to a contact internal floating-roof storage tank with a liquid-mounted primary seal.
	II	NEW: Option II - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal.
	III	Option III - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.
	IV(A)	Option A - Each storage tank must be fitted to a steam-regenerated carbon adsorption system.
	IV(B)	Option B - Each storage tank must be fitted to a thermal oxidation system.
IV-		EXISTING: Option IV - Each fixed-roof, external floating-roof, and internal floating-roof storage tank must be converted to a contact internal floating-roof storage tank with a liquid-mounted primary seal and a continuous secondary seal.
	III	NEW: Option III - Each storage tank must have a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal.
	IV(A)	Option A - Each storage tank must be fitted to a steam-regenerated carbon adsorption system.
	IV(B)	Option B - Each storage tank must be fitted to a thermal oxidation system.

(continued)

Table 5-9. Concluded

V(A)-	EXISTING: Option A - Each storage tank must be fitted to a steam-regenerated carbon adsorption system.	
	IV(A)	NEW: Option A - Each storage tank must be fitted to a steam-regenerated carbon adsorption system.
	IV(B)	NEW: Option B - Each storage tank must be fitted to a thermal oxidation system.
V(B)-	EXISTING: Option B - Each storage tank must be fitted to a thermal oxidation system.	
	IV(A)	NEW: Option A - Each storage tank must be fitted to a steam-regenerated carbon adsorption system.
	IV(B)	NEW: Option B - Each storage tank must be fitted to a thermal oxidation system.

6. ENVIRONMENTAL AND ENERGY IMPACTS

6.1 INTRODUCTION

This chapter discusses the environmental and energy impacts associated with each of the 26 regulatory alternatives summarized in Table 5-9. The impacts are discussed with regard to air quality, water quality and rates of consumption, solid waste, and energy requirements. Both beneficial and adverse impacts are presented, with the major emphasis on the incremental impacts of the regulatory alternatives.

6.2 AIR POLLUTION IMPACTS

6.2.1 Modeling Results

The air quality impacts of applying each of the control options in Tables 5-1 and 5-2 to each of the model benzene storage plants in Table 5-5 were evaluated using the Industrial Source Complex (ISC) dispersion model.[1] The ISC dispersion model predicts the ambient concentrations that would result from air pollutant sources, based on meteorological data and the characteristics of the emitting sources (such as the emissions rate, stack height, and stack gas temperature).

The maximum annual benzene concentrations associated with existing facilities are shown in Table 6-1. These concentrations were estimated using the annual emissions for existing facilities in Table 6-2. The maximum annual concentrations associated with new facilities are presented in Table 6-3. These concentrations were estimated using the annual emissions for new facilities in Table 6-4. The ambient concentrations are highest for the control options requiring the use of a carbon adsorption vapor control system (Options IV(A) and V(A) for new and existing tanks, respectively) because benzene emissions from carbon adsorption units have no thermal buoyancy and minimal vertical momentum. Consequently,

Table 6-1. MAXIMUM ANNUAL BENZENE CONCENTRATIONS FOR EXISTING MODEL FACILITIES - 0.1 KILOMETERS FROM THE SOURCE BOUNDARY[1]

(ug/m^3)

Control option	Large benzene producer	Small benzene producer	Benzene consumer	Bulk storage terminal
0 (Baseline)[a]	16.8	7.29	5.40	5.40
I	16.8	7.22	5.40	5.40
II	15.9	7.22	5.40	5.40
III	5.13	5.71	1.82	1.82
IV	3.13	3.49	1.10	1.10
V(A)[b]	35.6	8.78	4.33	4.33
V(B)[c]	4.72	1.17	0.565	0.565
VI	0	0	0	0

[a] No additional standard.

[b] Steam-regenerated carbon adsorption system.

[c] Thermal oxidation system.

Table 6-2. EMISSIONS FOR CONTROL OPTIONS - EXISTING FACILITIES (FIXED-ROOF TANK CTG AS BASELINE)

(Mg/yr)

Control option	Large benzene producer	Small benzene producer	Benzene consumer	Bulk storage terminal
0 (Baseline)[a]	44	13	6.5	6.5
I	44	12 - 13[b]	6.5	6.5
II	36	12 - 13[b]	6.5	6.5
III	13	6.3	3.3	3.3
IV	7.7	3.9	2.0	2.0
V(A)[c]	9.1	2.2	1.1	1.1
V(B)[d]	6.8	1.7	0.83	0.83
VI	0	0	0	0

[a] No additional standard.

[b] Range of emissions for control option which allows the use of contact and noncontact internal floating roofs, respectively, in affected tanks.

[c] Steam-regenerated carbon adsorption system.

[d] Thermal oxidation system.

Table 6-3. MAXIMUM ANNUAL BENZENE CONCENTRATIONS FOR NEW MODEL FACILITIES - 0.1 KILOMETERS FROM THE SOURCE BOUNDARY[1]

(ug/m^3)

Control option	Large benzene producer	Small benzene producer	Benzene consumer	Bulk storage terminal
0 (Baseline)[a, b]	17.0	19.2	6.78	6.78
I	17.0	19.1	6.78	6.78
II	5.13	5.71	1.82	1.82
III	3.13	3.49	1.10	1.10
IV(A)[c]	35.6	8.78	4.33	4.33
IV(b)[d]	4.72	1.17	0.565	0.565
V	0	0	0	0

[a] No additional standard.

[b] Baseline concentrations for new model facilities are higher than those for existing facilities because new facilities are assumed to only comply with the minimum requirements of the Petroleum Liquid Storage Tanks NSPS; therefore, all internal floating-roof tanks are assumed to have noncontact internal floating roofs.

[c] Steam-regenerated carbon adsorption system.

[d] Thermal oxidation system.

Table 6-4. EMISSIONS FOR CONTROL OPTIONS - NEW FACILITIES (PETROLEUM LIQUID STORAGE TANK NSPS AS BASELINE)

(Mg/yr)

Control option	Large benzene producer	Small benzene producer	Benzene consumer	Bulk storage terminal
0 (Baseline)[a]	40	21	11	11
I	40	20 - 21[b]	11	11
II	13	6.3	3.3	3.3
III	7.7	3.9	2.0	2.0
IV(A)[c]	9.1	2.2	1.1	1.1
IV(B)[d]	6.8	1.7	0.83	0.83
V	0	0	0	0

[a] No additional standard.

[b] Range of the emissions for control option which allows the use of contact and noncontact internal floating roofs, respectively, in affected tanks.

[c] Steam-regenerated carbon adsorption system.

[d] Thermal oxidation system.

in the absence of a tall stack, the emissions remain close to the ground where they undergo little mixing. Concentrations are significantly lower for the options requiring the use of a thermal oxidation system (Options IV(B) and V(B) for new and existing tanks, respectively) because the emissions from thermal oxidation units are discharged at elevated temperatures. Consequently, there is significant plume rise and good mixing of the pollutants.

6.2.2 Effects of Regulatory Alternatives on Nationwide Emissions

In order to evaluate the air pollution impacts in the years 1980, 1985, and 1990 associated with each of the 26 regulatory alternatives being considered, the numbers of new benzene storage facilities were estimated. These facilities include large benzene producers, small benzene producers, benzene consumers, and bulk storage terminals. Using the number of each type of facility existing in 1979 as the baseline, it was assumed that the number of new facilities is directly related to the projected growth rate of benzene usage from 1980 through 1990. Benzene usage is projected to increase at a rate of 5 percent per year over the next 10 years (see Section 7.1). Consequently, the number of new facilities was estimated using a growth rate of 5 percent per year, assuming a constant facility and tank utilization rate over the 10-year period. The number of facilities existing in 1979, as well as the projected number of new and existing facilities in 1980, 1985, and 1990, are shown in Table 6-5.

Based on these projections and the benzene emissions estimates from Tables 6-2 and 6-4 for existing and new facilities, respectively, the total nationwide benzene emissions for 1980, 1985, and 1990, were estimated. These estimates are presented in Tables 6-6, 6-7, and 6-8.

These tables show that the greatest emissions reductions would be obtained with the alternatives which require that each new and existing benzene storage tank be fitted to a vapor control system. (Alternatives V(A)-IV(A), V(A)-IV(B), V(B)-IV(A), and V(B)-IV(B)). The use of vapor control systems is expected to result in emissions reductions of approximately 90 percent in 1980, 1985, and 1990, when compared with the projected baseline emissions (Alternative 0-0) for each of these years.

Table 6-5. TOTAL PROJECTED NUMBER OF PLANTS WITH BENZENE STORAGE TANKS (1979-1990)

Year	Large benzene producer	Small benzene producer	Benzene consumer	Bulk storage terminal
1979[a]	28	34	77	4
1980	29.4	35.7	80.8	4.2
1985	37.5	45.6	103.2	5.4
1990	47.9	58.2	131.7	6.8

[a] Baseline year.

Table 6-6. NATIONWIDE EMISSIONS FROM NEW AND EXISTING BENZENE STORAGE TANKS IN 1980

(Mg/yr)

Control options for existing tanks	Control options for new tanks						
	0	I	II	III	IV(A)	IV(B)	V
0	2,300[a]	2,300	2,200	2,200	2,200	2,200	X
I	X[b]	2,300	2,200	2,200	2,200	2,200	X
II	X	X	2,000	2,000	2,000	2,000	X
III	X	X	890	870	870	860	X
IV	X	X	X	540	530	530	X
V(A)	X	X	X	X	440	430	X
V(B)	X	X	X	X	340	330	X
VI	X	X	X	X	X	X	X

[a] This includes 2200 Mg/yr from existing tanks and 100 Mg/yr from new tanks.

[b] Regulatory alternatives marked with an "X" have been eliminated from further consideration (see Section 5.2.2).

Table 6-7. NATIONWIDE EMISSIONS FROM NEW AND EXISTING BENZENE STORAGE TANKS IN 1985

(Mg/yr)

Control options for existing tanks	Control options for new tanks						
	0	I	II	III	IV(A)	IV(B)	V
0	3,100[a]	3,100	2,500	2,400	2,300	2,300	X
I	X[b]	3,100	2,500	2,300-2,400[c]	2,300	2,300	X
II	X	X	2,200-2,300[c]	2,100-2,200[c]	2,100	2,000-2,100[c]	X
III	X	X	1,100	1,000	990	950	X
IV	X	X	X	680	650	620	X
V(A)	X	X	X	X	560	530	X
V(B)	X	X	X	X	460	420	X
VI	X	X	X	X	X	X	X

[a] This includes 2,200 Mg/yr from existing tanks and 900 Mg/yr from new tanks.

[b] Regulatory alternatives marked with an "X" have been eliminated from further consideration (see Section 5.2.2).

[c] Range indicates emissions for alternative which allows the use of contact and noncontact internal floating roofs, respectively, in affected tanks.

Table 6-8. NATIONWIDE EMISSIONS FROM NEW AND EXISTING BENZENE STORAGE TANKS IN 1990

(Mg/yr)

Control options for existing tanks	Control options for new tanks						
	0	I	II	III	IV(A)	IV(B)	V
0	4,100[a]	4,100	2,800	2,600	2,500	2,400	X
I	X[b]	4,100	2,800	2,500-2,600[c]	2,500	2,400	X
II	X	X	2,500-2,600[c]	2,300	2,200-2,300[c]	2,400	X
III	X	X	1,400	1,200	1,100	1,100	X
IV	X	X	X	870	810	730	X
V(A)	X	X	X	X	720	640	X
V(B)	X	X	X	X	610	540	X
VI	X	X	X	X	X	X	X

[a] This includes 2,200 Mg/yr from existing tanks and 1,900 Mg/yr from new tanks.

[b] Regulatory alternatives marked with an "X" have been eliminated from further consideration (see Section 5.2.2).

[c] Range indicates emissions for alternative which allows the use of contact and noncontact internal floating roofs, respectively, in affected tanks.

liquid-mounted primary seal and a continuous secondary seal, would result in the largest emissions reduction of any of the alternatives not requiring the use of a vapor control system. Implementation of this alternative would result in about a 78 percent reduction of emissions in 1980, 1985, and 1990, when compared to the baseline emissions (Alternative 0-0) for each of these years.

The national emissions reductions for 1980, 1985, and 1990, are presented in Tables 6-9, 6-10, and 6-11, respectively.

6.2.3 Secondary Impacts on Air Quality

The option requiring the use of a thermal oxidation vapor control system may result in some secondary air quality impacts. However, because the emissions from a thermal oxidation unit are expected to be minimal during normal operation, the impacts should not be significant.

These impacts on air quality are associated with the use of natural gas or fuel oil to fire the thermal oxidation unit. A thermal oxidation unit which uses either natural gas or fuel oil as supplemental fuel will produce oxides of nitrogen (NO_x). Oxides of sulfur (SO_x) will also be produced with the use of fuel oil. The emissions from a typical thermal oxidation unit could be as large as 15,000 kilograms per year (kg/year) of SO_x and 6,000 kg/year of NO_x.

6.3 IMPACTS ON WATER QUALITY AND RATES OF CONSUMPTION

There could be significant impacts on water quality and the rates of consumption associated with those control options which require that each tank be fitted to either a carbon adsorption vapor control system (Options IV(A) and V(A) for new and existing tanks, respectively) or a thermal oxidation vapor control system (Options IV(B) and V(B) for new and existing tanks, respectively). A maximum of 9,100 liters of benzene-contaminated water per day of operation could be produced from the operation of a carbon adsorption system. As much as 5,700 liters per day could be produced from a thermal oxidation system.

A water seal is one source of benzene-contaminated water employed with both types of vapor control systems. A water seal is used to ensure that flashbacks do not propagate from the vapor control unit to the rest of the piping system. Either of the two vapor control systems would

Table 6-9. NATIONWIDE EMISSIONS REDUCTIONS FROM NEW AND EXISTING BENZENE STORAGE TANKS IN 1980

(Megagrams per year)

Control options for existing tanks	Control options for new tanks						
	0	I	II	III	IV(A)	IV(B)	V
0	0	0	100	100	100	100	X
I	X[a]	0	100	100	100	100	X
II	X	X	300	300	300	300	X
III	X	X	1,400	1,400	1,400	1,400	X
IV	X	X	X	1,800	1,800	1,800	X
V(A)	X	X	X	X	1,900	1,900	X
V(B)	X	X	X	X	2,000	2,000	X
VI	X	X	X	X	X	X	X

[a] Regulatory alternatives marked with an "X" have been eliminated from further consideration (see Section 5.2.2).

Table 6-10. NATIONWIDE EMISSIONS REDUCTION FROM NEW AND EXISTING BENZENE STORAGE TANKS IN 1985

(Megagrams per year)

Control options for existing tanks	Control options for new tanks						
	0	I	II	III	IV(A)	IV(B)	V
0	0	0	600	700	800	800	X
I	X[a]	0	600	700-800[b]	800	800	X
II	X	X	800-900[b]	900-1,000[b]	1,000	1,000-1,100[b]	X
III	X	X	2,000	2,100	2,100	2,200	X
IV	X	X	X	2,400	2,400	2,500	X
V(A)	X	X	X	X	2,500	2,600	X
V(B)	X	X	X	X	2,600	2,700	X
VI	X	X	X	X	X	X	X

[a] Regulatory alternatives marked with an "X" have been eliminated from further consideration (see Section 5.2.2).

[b] Range indicates emissions reduction for alternative which allows the use of noncontact and contact internal floating roofs, respectively, in affected tanks.

Table 6-11. NATIONWIDE EMISSIONS REDUCTIONS FROM NEW AND EXISTING BENZENE STORAGE TANKS IN 1990

(Megagrams per year)

Control options for existing tanks	Control options for new tanks						
	0	I	II	III	IV(A)	IV(B)	V
0	0	0	1,300	1,500	1,600	1,700	X
I	X[a]	0	1,300	1,500-1,600[b]	1,600	1,700	X
II	X	X	1,500-1,600[b]	1,800	1,800-1,900[b]	1,900	X
III	X	X	2,700	2,900	3,000	3,000	X
IV	X	X	X	3,200	3,300	3,400	X
V(A)	X	X	X	X	3,400	3,500	X
V(B)	X	X	X	X	3,500	3,600	X
VI	X	X	X	X	X	X	X

[a] Regulatory alternatives marked with an "X" have been eliminated from further consideration (see Section 5.2.2).

[b] Range indicates emissions reduction for alternative which allows the use of noncontact and contact internal floating roofs, respectively, in affected tanks.

require two water seals, resulting in the production of as much as 5,700 liters per day of benzene-contaminated water. Carbon adsorption vapor control systems can have an additional source of water pollution if the carbon bed is regenerated using steam. In a steam-regenerated carbon adsorption system steam circulated through the carbon bed heats the carbon and raises the benzene vapor pressure. The benzene evolved in this process is removed along with the steam, and the steam-benzene mixture is condensed and decanted. The recovered benzene is returned to storage while the water, which is contaminated with benzene, is sent to the plant wastewater system for treatment and disposal. As much as 3,400 liters per day of benzene-contaminated water could be produced with the use of steam regeneration.

6.4 SOLID WASTE DISPOSAL IMPACTS

Only the control options requiring the use of a carbon adsorption vapor control system (Options IV(A) and V(A) for new and existing tanks, respectively) will likely result in any significant impacts on solid waste disposal. The only impacts would be associated with the handling of spent carbon from the adsorption unit. Typically, the spent carbon, which is normally replaced approximately once every 10 to 15 years, is transported to a facility for reclamation and reactivation.[2] There would be no solid waste impact associated with this operation. However, this material could be disposed of in a landfill which would result in a solid waste disposal impact. Because the owner or operator of a carbon adsorption unit is most likely to have the carbon reclaimed and reactivated, no impact on solid waste disposal is expected with the use of a carbon adsorption system.

6.5 ENERGY IMPACTS

The only control options having any energy impacts are those which require that each tank be fitted to a carbon adsorption vapor control system (Options IV(A) and V(A) for new and existing tanks, respectively) or a thermal oxidation vapor control system (Options IV(B) and V(B) for new and existing tanks, respectively). Use of a carbon adsorption system will require electricity to power blowers for collecting and transferring the air-benzene vapor mixture from the storage tank to the carbon adsorption unit. Low pressure steam will be required to regenerate the carbon bed. The steam and electrical requirements for each of the model facilities were calculated using vendor quotes and engineering estimates. The energy equivalents of steam and electricity are shown in Table 6-12.

Use of a thermal oxidation system to dispose of benzene vapors will require electricity to power blowers for transferring the air-benzene vapor mixture to the oxidation unit, and supplemental fuel (natural gas assumed) to ignite and sustain the combustion process. The electrical requirements were calculated using both vendor quotes and engineering estimates, while the natural gas requirements were calculated using only engineering estimates. Table 6-13 shows the natural gas and electrical energy requirements for each of the four model facilities.

6.6 OTHER ENVIRONMENTAL CONCERNS

6.6.1 Irreversible and Irretrievable Commitment of Resources

The most significant commitment of resources would be required with the use of a carbon adsorption or thermal oxidation vapor control system. Both of these vapor control systems would require electricity to operate blowers for transferring vapors from the storage tanks to the vapor control unit. Use of a carbon adsorption system would also require a supply of water for generating steam to desorb recovered benzene from the carbon bed. Natural gas or other supplemental fuel would be required to ignite and sustain the combustion process with the use of a thermal oxidation system. The total nationwide energy consumption for 1985 associated with the use of vapor control systems would range from 0.7 to 0.8 petajoules per year.

6.6.2 Environmental Impacts of Delayed Standards

The only environmental impact associated with a delay in proposing and promulgating standards for new and existing benzene storage tanks would be an increase in the quantity of benzene emitted from storage tanks as more tanks are constructed. Current uncontrolled benzene emissions from benzene storage tanks are estimated to be approximately 2,200 megagrams per year. These emissions are projected to increase to 2,300 megagrams per year in 1980 with the construction of new storage tanks. By 1985, these emissions are estimated to be approximately 3,100 megagrams per

Table 6-12. ENERGY REQUIRED TO OPERATE A STEAM-REGENERATED CARBON ADSORPTION SYSTEM AT EACH MODEL BENZENE STORAGE FACILITY[a]

(TJ/yr)

Model facility	Steam	Electricity
Large benzene producer	3.4	0.22
Small benzene producer	3.4	0.22
Benzene consumer or bulk storage terminal	3.4	0.22

[a] Carbon adsorption system for each model facility is sized for a maximum vapor flow of 0.126 m^3/s for a 2000 gpm storage tank filling rate.

Table 6-13. ENERGY REQUIRED TO OPERATE A THERMAL OXIDATION SYSTEM AT EACH MODEL BENZENE STORAGE FACILITY[a]

(TJ/yr)

Model facility	Natural gas	Electricity
Large benzene producer	4.1	0.18
Small benzene producer	4.1	0.18
Benzene consumer or bulk storage terminal	4.1	0.18

[a] Carbon adsorption system for each model facility is sized for a maximum vapor flow of 0.126 m^3/s for a 2000 gpm storage tank filling rate.

year, an increase of 800 megagrams per year over the 1980 emissions rate. The uncontrolled emissions are projected to increase to 4,100 megagrams per year by 1990.

6.7 REFERENCES FOR CHAPTER 6

1. H. E. Cramer Company, Inc. Calculated Air Quality Impact of Emissions from Benzene Storage Facilities. Prepared for the U.S. Environmental Protection Agency. Report No. TR-80-141-04. Salt Lake City, Utah. July 1980.

2. U.S. Environmental Protection Agency. Benzene Emissions from Maleic Anhydride Industry - Background Information for Proposed Standards. EPA-450/3-80-001a. Research Triangle Park, North Carolina. February 1980.

7. ECONOMIC ANALYSIS

7.1 INDUSTRY PROFILE

Although the subject of this standard is benzene storage, the supply and demand for benzene manufactured in the United States are the major factors affecting both the present number of storage tanks and the number that will be built in the future. In addition, even though some benzene is stored in tanks owned by independent terminal operators, a majority of the companies that produce benzene, consume benzene, or both also own storage tanks; thus, these companies will bear most of the control costs. For these reasons, the industry profile presents data on the production and consumption of benzene as a means of addressing the impacts of regulations on the owners and operators of benzene storage tanks.

7.1.1 Benzene Production, Sales, and Capacity

Figures for 1978 put U.S. benzene production from all sources at 4,974 gigagrams (1,488 million gallons).[1] This figure includes benzene made from coke-oven light oil, a byproduct of steel manufacturing. Although benzene stored at coke-oven byproduct facilities would not be affected by any standard recommended as a result of this study, production and company data are included to present an overview of the benzene industry.

Table 7-1 summarizes historical production, sales quantities, and sales values for benzene in the United States. Production of benzene from coke-oven light oil is distinguished from petroleum-based benzene. The percentage shares of total production made from these two types of raw materials have reversed since 1950, when coke-oven light oil was the source of 95 percent of the benzene produced. In 1978, this source accounted for less than 4 percent of the benzene produced.

Figure 7-1 graphically illustrates the growth in production and sales quantities since 1950. Production and sales trend lines exhibit

Table 7-1. HISTORICAL U. S. BENZENE PRODUCTION AND SALES[2]

Year	Production						Sales		
	From coke-oven operators		From petroleum		Total		Quantity		Value
	Gigagrams	Million gallons	Gigagrams	Million gallons	Gigagrams	Million gallons	Gigagrams	Million gallons	Million dollars
1978	178.8	53.5	4,795.3	1,435.0	4,973.7	1,488.4	2,529.3	756.9	558.4
1977	215.9	64.6	4,581.7	1,371.1	4,796	1,435.7	2,200.5	658.5	504.3
1976	201.8	60.4	4,560.7	1,364.8	4,760	1,425.2	2,129.6	637.3	489.5
1975	217.5	65.1	3,203.4	958.9	3,420	1,023.9	1,829.6	547.5	387.0
1974	274.3	82.1	4,698.7	1,406.1	4,971	1,488.3	2,534.6	788.4	527.8
1973	287.0	85.9	4,569.0	1,367.3	4,854	1,453.3	2,403.6	719.3	206.8
1972	266.7	79.8	3,918.4	1,172.6	4,185.1	1,252.4	2,269.6	679.2	138.5
1971	240.9	72.1	3,354.3	1,003.8	3,595.3	1,075.9	1,980.6	592.7	118.9
1970	312.4	93.5	3,642.4	1,090	3,956.5	1,184	2,185.4	654.0	143.3
1969	339.8	101.7	3,756.0	1,124	4,096.9	1,226	2,256.3	675.2	147.8
1968	309.4	92.6	3,101.1	928	3,411.8	1,021	2,051.8	614.0	129.7
1967	302.8	90.6	2,936.3	878.7	3,239.1	969.3	1,884.4	563.9	135.2
1966	380.6	113.9	2,811.3	841.3	3,191.9	955.2	2,025.0	606.0	147.3
1965	407.3	121.9	2,355.9	705.0	2,763.2	826.9	1,706.9	510.8	123.3
1964	397.3	118.9	2,042.8	611.3	2,440.1	730.2	1,550.5	464.0	104.2
1963	409.4	122.5	1,757.4	525.9	2,166.7	648.4	1,406.5	420.9	96.3
1962	412.4	123.4	1,397.1	418.1	1,809.5	541.5	1,352.4	404.7	99.5
1961	435.8	130.4	1,379.4	412.8	1,815.2	543.2	1,406.8	421.0	134.1
1960	492.6	147.4	1,033.2	309.2	1,525.8	456.6	1,261.1	377.4	117.6
1959	435.4	130.3	697.7	208.8	1,133.2	339.1	1,041.1	330.4	96.2
1958	430.4	128.8	474.8	142.1	904.9	270.8	813.0	243.3	79.3
1957	648.6	194.1	388.3	116.2	1,036.6	310.2	924.0	276.5	98.0
1956	632.9	189.4	372.9	111.6	1,005.8	301.0	953.7	285.4	102.8
1955	632.2	189.2	329.5	98.6	961.7	287.8	884.9	264.8	97.5
1954	527.3	157.8	307.1	91.9	834.4	249.7	685.7	205.2	83.6
1953	661.0	197.8	210.5	63.0	871.5	260.8	748.2	233.9	95.9
1952	581.8	174.1	118.5	35.5	700.4	209.6	725.1	217.0	83.2
1951	658.3	197.0	108.9	32.6	766.9	229.5	799.3	239.2	84.4
1950	615.5	184.2	33.8	10.1	649.3	194.3	616.2	184.4	47.1

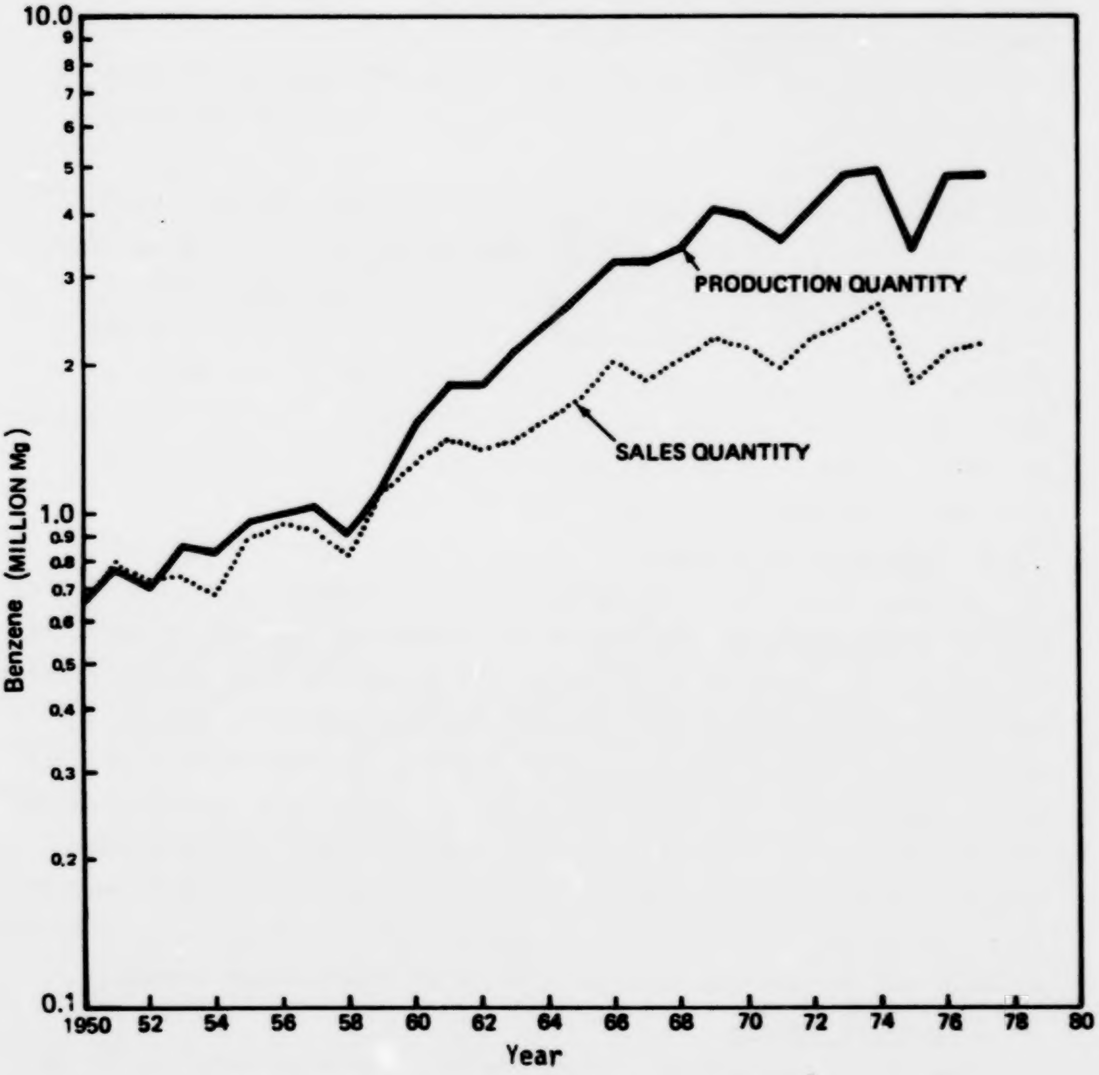

Figure 7-1. Benzene production, sales.[2]

cyclic behavior, but their previous peaks tend to be exceeded every 4 or 5 years. Overall growth is about 5 percent per year. The widening gap between production and sales quantities since the late 1950's indicates the increasing prevalence of captive consumption. Captive consumption is a situation where a company uses the benzene it manufacturers rather than sells it. In recent years, over one-half of the benzene produced has been captively consumed.

The trends exhibited by the sales value each year corresponded to sales volume until 1973. In 1973 the sales values increased sharply because of higher unit sales values.

Table 7-2 summarizes recent and historical capacity utilization rates for benzene. The utilization rate has varied (59 to 88 percent) in a roughly cyclic manner over the years, but has remained relatively constant since 1972. Based on quarterly-reported rates for the past 2 years, the utilization rate peaked at 79 percent in the beginning of 1977; the utilization rate then dipped to 67 percent in the third quarter of 1978. In the first quarter of 1979, the utilization rate began to rise again, reaching 70 percent.

7.1.2 Methods of Manufacture

Benzene is manufactured using five major methods. Four out of five methods employed in the manufacture of benzene use refinery products as the feedstock. These methods include (1) extraction from catalytic reformate, (2) toluene dealkylation, (3) toluene disproportionation, and (4) the processing of benzene from pyrolysis gasoline. A fifth method involves processing benzene from coke-oven light oil, which is a byproduct of the conversion of coal into coke for steel manufacturing. In most cases, benzene producers obtain the raw material from which benzene is made from their own refinery or manufacturing operations. In other cases, a benzene producer may buy benzene-containing material from another source.

7.1.3 Uses of Benzene

Benzene is used almost exclusively as a feedstock material in the production of other chemicals. Twenty-five percent of these chemicals are ultimately used in consumer goods, including packaging, toys, sporting goods, disposables, novelties, and other small manufactured items.[3] The

Table 7-2. BENZENE CAPACITY UTILIZATION RATES

Period	Capacity utilization rate (percent)
A. Recent rates[3]	
1st Quarter 1979	70
3rd Quarter 1978	67
1st Quarter 1978	73
3rd Quarter 1977	75
1st Quarter 1977	79
B. Historical rates[2,3,16]	
1978	68
1977	72
1976	79
1975	59
1974	85
1973	88
1972	79

major benzene-derived chemicals used in manufacturing these products include styrenics such as polystyrene, epoxy resins, acrylonitrile-butadiene-styrene (ABS), and styrene acrylonitrile (SAN). Seventeen percent of the derivatives, including nylon fibers and resins, ABS, polystyrene, phenolics, and epoxies, are used in the manufacture of household goods such as furniture, appliances, and carpeting.[3] The transportation industry also uses 17 percent of the benzene derivatives produced.[3] Plastics, fibers, elastomers, and rubber are used in the production of boats, airplanes, trucks, and automobiles.[3]

As shown in Table 7-3, the manufacture in the United States of three chemical products consumed 83 percent of the benzene produced in 1976. These products are ethylbenzene from which styrene is made, cumene from which phenol is made, and cyclohexane. Other products derived from benzene include chlorobenzene, nitrobenzene, maleic anhydride, and detergent alkylate.

7.1.4 Benzene Prices

As shown in Table 7-4, benzene prices stayed between \$0.06 and \$0.09 per kilogram (\$0.20 and \$0.30 per gallon, respectively) from 1965 to 1973. In response to the 1974 oil embargo, prices jumped to almost \$0.20 per kilogram (\$0.67 per gallon). Although the average benzene price in 1978 declined to about \$0.22 per kilogram (\$0.74 per gallon) compared to the 1977 price of about \$0.23 per kilogram (\$0.76 per gallon), the oil shortage in late 1978 sent prices to \$0.39 per kilogram (\$1.30 per gallon), and in 1979 some spot prices exceeded \$0.60 per kilogram (\$2.00 per gallon).

This price fluctuation indicates the close relationship between benzene and crude oil prices. Benzene made from coke-oven light oil also experiences sharp price increases as a result of market factors.

7.1.5 Market Factors that Affect the Benzene Industry

Benzene is contained in chemical feedstock that could be diverted to other uses. Therefore, the end product derived from benzene must be profitable enough to justify recovering benzene from that feedstock material. Whether these materials will be diverted from other uses to the manufacture of benzene depends on a number of factors. These factors

Table 7-3. PERCENT OF 1976 BENZENE PRODUCTION USED IN THE MANUFACTURE OF MAJOR BENZENE-CONSUMING PRODUCTS[6]

Benzene consuming product	Percent of 1976 benzene production used in the product's manufacture
Ethylbenzene	51
Cumene	17
Cyclohexane	15
All others	17

Table 7-4. UNIT SALES VALUE OF BENZENE[2]

Year	Unit sales value[a]			
	Petroleum benzene		Coke-oven benzene	
	Cents per kilogram	Cents per gallon	Cents per kilogram	Cents per gallon
1978	22.1	74.0	22.1	74.0
1977	22.7	76.0	24.5	82.0
1976	22.9	76.5	23.8	79.4
1975	21.0	70.1	22.4	75.0
1974	19.7	65.8	22.8	76.3
1973	8.7	29.0	8.0	26.7
1972	6.0	20.0	6.0	20.0
1971	6.0	20.0	6.0	20.0
1970	6.6	22.0	6.3	21.0
1969	6.6	22.0	6.6	22.0
1968	6.3	21.0	6.6	22.0
1967	7.2	24.0	7.2	24.0
1966	7.2	24.0	7.2	24.0
1965	7.2	24.0	6.9	23.0

[a] Total sales value divided by total sales quantity.

include the value of the material in which the benzene is contained, the value of the unrecovered benzene, and the cost of recovery.

The gasoline market is one factor that directly affects the benzene industry in the manner just discussed. Both catalytic reformate and toluene are used as sources from which high octane compounds for gasoline are produced. When these materials yield higher profits when they are employed in the production of gasoline than when benzene is recovered from them, they are more likely to be diverted for use in gasoline.

Demand for benzene is also affected by general economic conditions because of its uses as a feedstock in other products. The automobile industry's behavior affects benzene demand because styrene is used in tires. Similarly, the construction industry also has an effect on the demand for benzene because of the use of aniline in the manufacture of building insulation materials, and the use of benzene-based fibers for manufacturing.

Table 7-5 lists the products made from benzene for which alternate chemicals can be substituted for benzene as a feedstock. Essentially all benzene substitutes used are derived from either petroleum or natural gas. Therefore, any move to switch from benzene to these alternate feedstocks cannot be expected to alter the close relationship between the costs of these products and the cost of crude oil or natural gas.

7.1.6 Import/Export Considerations

Benzene imports do not represent a large portion of the total benzene production. In 1976, net benzene imports of 56.8 gigagrams (17 million gallons) represented only 1 percent of the total 1976 supply. Should benzene-containing material be diverted to gasoline manufacture in the United States, resulting in a tightened benzene supply (see Section 7.1.5), there is a possibility that benzene imports would increase. However, the overall import/export situation is not expected to be a long-term major factor in the domestic supply of benzene.[7]

As shown in Table 7-6, during the 1950's more benzene was imported than exported. During the 1960's exports began to exceed imports, reaching a maximum net export level of 256 gigagrams (76.6 million gallons) in 1967. This situation was the result of increasing overseas chemical operations that used U.S.-produced benzene until local supplies became available.[7] Once these supplies came on-line in the 1970's, U.S. imports

Table 7-5. SUBSTITUTES FOR PRODUCTS MADE FROM BENZENE[8]

Benzene-based product	Benzene substitute
Maleic anhydride	Oxidation of n-butane; byproduct of phthalic anhydride (xylene derivative)
Ethylbenzene	Mixed xylene streams
Cyclohexane	Natural gas
Biphenyl	Byproduct of toluene dealkylation

Table 7-6. UNITED STATES TRADE IN BENZENE[7]

Year	Imports					Exports					Net trade balance		
	Quantity		Value	Unit value		Quantity		Value	Unit value		Quantity		Value
	Gigagrams	Million gallons	Million dollars	Cents per kilogram	Cents per gallon	Gigagrams	Million gallons	Million gallons	Cents per kilogram	Cents per gallon	Gigagrams	Million gallons	Million dollars
1976	176.4	52.8	38.3	22.0	73	119.6	35.8	25.9	21.7	72	- 56.8	-17.0	-12.4
1975	234.9	70.3	50.9	21.7	72	60.1	18.0	10.2	17.2	57	-174.8	-52.3	-40.7
1974	341.9	102.3	111.7	32.9	109	76.2	22.8	24.9	32.9	109	-265.7	-79.5	-86.8
1973	173.4	51.9	14.7	8.5	28	99.6	29.8	12.3	12.4	41	- 73.9	-22.1	- 2.4
1972	317.8	95.1	17.4	5.4	18	96.9	29.0	6.3	6.6	22	-220.9	-66.1	-11.1
1971	256.3	76.7	13.9	6.3	21	142.4	42.6	8.4	6.0	20	-114.0	-34.1	- 5.5
1970	174.8	52.3	10.8	6.3	21	223.6	66.9	14.2	6.3	21	+ 48.8	+14.6	+ 3.4
1969	203.2	60.8	12.8	6.3	21	306.8	91.8	18.4	6.0	20	+103.6	+31.0	+ 5.6
1968	109.9	32.9	6.9	7.2	24	277.7	83.1	15.9	5.7	19	+167.8	+50.2	+ 9.0
1967	85.2	25.5	6.2	--	--	341.2	102.1	21.8	6.3	21	+256.0	+76.6	+15.6
1966	76.5	22.9	--	--	--	324.1	97.0	20.1	6.3	21	+247.6	+74.1	--
1965	82.2	24.6	--	--	--	151.4	45.3	10.7	7.2	24	+ 69.2	+20.7	--
1964	51.1	15.3	--	--	--	291.7	87.3	--	--	--	+240.6	+72.0	--
1963	43.8	13.1	--	--	--	216.2	64.7	--	--	--	+172.4	+51.6	--
1962	71.5	21.4	--	--	--	138.0	41.3	--	--	--	66.5	+19.9	--
1961	62.2	18.6	--	--	--	155.4	46.5	--	--	--	93.2	+27.9	--
1960	126.3	37.8	--	--	--	78.9	23.6	--	--	--	- 47.5	-14.2	--
1959	182.1	54.5	--	--	--	24.4	7.3	--	--	--	-157.7	-47.2	--
1958	148.7	44.5	--	--	--	38.4	11.5	--	--	--	-110.3	-33.0	--
1957	175.8	52.6	--	--	--	9.0	2.7	--	--	--	-166.7	-49.9	--
1956	220.9	66.1	--	--	--	9.0	2.7	--	--	--	-211.9	-63.4	--
1955	101.9	30.5	--	--	--	8.4	2.5	--	--	--	- 93.6	-28.0	--
1954	39.8	11.9	--	--	--	19.7	5.9	--	--	--	- 20.0	- 6.0	--
1953	65.5	19.6	--	--	--	4.0	1.2	--	--	--	- 61.5	-18.4	--
1952	138.7	41.5	--	--	--	0.7	0.2	--	--	--	-138.0	-41.3	--
1951	217.5	65.1	--	--	--	1.0	0.3	--	--	--	-216.5	-64.8	--
1950	73.9	22.1	--	--	--	4.3	1.3	--	--	--	- 69.5	-20.8	--

again exceeded exports. U.S. demand for imported benzene continued despite price increases in 1974.

7.1.7 Benzene-Producing Companies

Table 7-7 lists 37 companies that produced benzene in 1976. Currently, 28 of the companies are in the petroleum business, five are steel companies, and three are chemical companies. The remaining company is a joint venture between one petroleum company and two chemical companies.

Benzene production is fairly concentrated geographically, with over 80 percent of the production capacity located in five states or territories: Texas, Puerto Rico, Louisiana, Pennsylvania, and the Virgin Islands. Table 7-8 gives the percentage of production capacity located in each state. Figure 7-2 geographically locates these percentages.

The benzene industry is not monopolized by one company. Table 7-9 shows each company's share of the total national production capacity. No single company exceeds a 10 percent share, and it takes the combined shares of 15 companies to account for 80 percent of the total capacity.

Almost all benzene-producing companies have sales exceeding one billion dollars annually. As illustrated in Table 7-10, benzene production does not represent a large percentage of these companies' total sales. Benzene production is greater than a 5 percent share of sales for only two companies.

Commonwealth Oil Refining Company, which has the largest benzene production capacity and the greatest benzene-production-to-total-sales ratio, has been operating under Chapter 11 of the Federal Bankruptcy Act since March 2, 1978. The company is trying to financially recover but is also being considered for acquisition by both the Charter Company and the Arabian Seasoil Corporation.

7.1.8 Replacement Rate of Equipment

The replacement rate of benzene-manufacturing equipment and benzene storage equipment is low. This is because companies tend to refurbish their equipment on a continual basis rather than purchase replacements. This practice is characteristic of most refinery operations.

7.1.9 Benzene-Consuming Companies

Tables 7-11 through 7-13 list companies that manufacture ethylbenzene and styrene, cyclohexane, and cumene. These products represent

Table 7-7. BENZENE-PRODUCING COMPANIES[9]

Company and location	Annual benzene capacity as of January 1, 1977		
	Gigagrams	Million gallons	Million pounds
Amerada Hess Corporation			
Hess Oil Virgin Islands Corporation (subsidiary)			
St. Croix, VI	217	65	479
American Petrofina Inc.			
American Petrofina Co. of Texas, subsidiary			
Port Arthur, Texas	67	20	147
American Petrofina Co. of California (joint venture)			
Beaumont, Texas	74	22	162
Cosden Oil & Chemical Co., subsidiary			
Big Spring, Texas	194	58	427
Armco Steel Corporation[a]			
Middletown Ohio	10	3	22
Ashland Oil Inc.			
Ashland Chemical Company, Division			
Petrochemical Division			
Ashland (Catlettsburg), Kentucky	214	64	471
North Tonewanda (Buffalo), New York	77	23	169
Atlantic Richfield Company			
ARCO Chemical Co., Division			
Channelview, Texas	107	32	236
Houston, Texas	140	42	309
Wilmington, California	40	12	88
Bethlehem Steel Corporation[a]			
Bethlehem, Pennsylvania	13	4	29
Lackawanna, New York	-	-	-

(continued)

Table 7-7. Continued

Company and location	Annual benzene capacity as of January 1, 1977		
	Gigagrams	Million gallons	Million pounds
Bethlehem Steel Corporation (Continued)			
Sparrows Point, Maryland	50	15	110
CF&I Steel Corporation[a]			
Pueblo, Colorado	10	3	22
The Charter Company			
Charter Oil Co., subsidiary			
Charter Chemicals-Charter International Oil Co., subsidiary			
Houston, Texas	17	5	37
Cities Service Company			
Lake Charles, Louisiana	84	25	184
Coastal States Corporation			
Coastal States Gas Producing Co.			
Coastal States Petrochemical Co., subsidiary			
Corpus Christi, Texas	234	70	516
Commonwealth Oil Refining Company, Inc.			
Commonwealth Petrochemicals, Inc., subsidiary			
Penuelas, Puerto Rico	618	185	1,363
Corpus Christi Petrochemicals Co.			
Champlin Petroleum Co. (37.5%)/ Imperial Chemical Industries Ltd. (37.5%)/Soltex Polymer Corp. (25%) (Joint Venture)	The companies are constructing a 1.2 billion pound per year ethylene factory based on gas, oil, and naphtha. Benzene capacity is estimated to be 100 gigagrams (30 million gallons) per year. Estimated completion date is early 1980.		

(continued)

Table 7-7. Continued

Company and location	Annual benzene capacity as of January 1, 1977		
	Gigagrams	Million gallons	Million pounds
Crown Central Petroleum Corp.			
Pasadena, Texas	77	23	169
The Dow Chemical Company			
Dow Chemical U.S.A.			
Bay City, Michigan	100	30	221
Freeport, Texas	167	50	368
Plaquemine, Louisiana	-	-	-
Exxon Corporation			
Exxon Chemical Co., Division			
Exxon Chemical Co. U.S.A.			
Baton Rouge, Louisiana	234	70	516
Baytown, Texas	200	60	442
Getty Oil Company			
Getty Refining & Marketing Co. subsidiary			
El Dorado, Kansas	43	13	96
Gulf Oil Corporation			
Gulf Oil Chemicals Co., Division			
Petrochemicals Division			
Alliance, Louisiana	224	67	493
Philadelphia, Pennsylvania	124	37	273
Port Arthur, Texas	134	40	295
Independent Refining Corporation			
Winnie, Texas	10	3	22
Kerr-McGee Corporation			
Southwestern Refining Co., Inc., subsidiary			
Corpus Christi, Texas	53	16	118

(continued)

Table 7-7. Continued

Company and location	Annual benzene capacity as of January 1, 1977 Gigagrams	Million gallons	Million pounds
The LTV Corporation[a]			
Jones & Laughlin Industries, Inc.			
Jones & Laughlin Steel Corp., subsidiary			
Aliquippa, Pennsylvania	33	10	74
Marathon Oil Company			
Texas City, Texas	23	7	52
Mobil Corporation			
Mobil Oil Corporation			
Mobil Chemical Co., Division			
Petrochemicals Division			
Beaumont, Texas	200	60	442
Monsanto Company			
Monsanto Chemical Intermediates Company			
Alvin (Chocolate Bayou)/ Texas City, Texas	284	85	626
Pennzoil Company			
Atlas Processing Co., subsidiary			
Shreveport, Louisiana	50	15	110
Phillips Petroleum Company			
Phillips Chemical Company			
Sweeny, Texas	33	10	74
Phillips Puerto Rico Core, Inc., subsidiary			
Guayama, Puerto Rico	368	110	810

(continued)

Table 7-7. Continued

Company and location	Annual benzene capacity as of January 1, 1977		
	Gigagrams	Million gallons	Million pounds
Quintana-Howell			
(Joint venture of Quintana Refinery Company and the Howell Corporation)			
Corpus Christi, Texas	23	7	52
Shell Oil Company			
Shell Chemical Company, Division			
Deer Park, Texas	301	90	663
Odessa, Texas	40	12	88
Wood River, Illinois	150	45	331
Standard Oil Company of California			
Chevron Chemical Company, subsidiary			
El Segundo, California	77	23	169
Standard Oil Company (Indiana)			
Amoco Oil Company, subsidiary			
Texas City, Texas	284	85	626
The Standard Oil Company (Ohio)			
BP Oil Inc., subsidiary			
Marcus Hook, Pennsylvania	27	8	59
Sun Company, Inc.			
Sun Oil Company of Pennsylvania, subsidiary			
Sun Petroleum Products Company, subsidiary			
Corpus Christi, Texas	127	38	280
Marcus Hook Pennsylvania	97	29	214
Toledo, Ohio	164	49	361
Tulsa, Oklahoma	80	24	177

(continued)

Table 7-7. Concluded

Company and location	Annual benzene capacity as of January 1, 1977		
	Gigagrams	Million gallons	Million pounds
Tenneco, Inc.			
Tenneco Oil Company, Division			
Chalmette, Louisiana	33	10	74
Texaco, Inc.			
Port Arthur, Texas	150	45	331
Westville, New Jersey	117	35	258
Union Carbide Corporation			
Chemicals and Plastics, Division			
Taft, Louisiana	234	70	516
Union Carbide Carbide, Inc., subsidiary			
Penuelas, Puerto Rico	-	-	-
Union Oil Company of California			
Chicago (Lemont), Illinois	57	17	125
Union Pacific Corporation			
Champlin Petroleum Company, subsidiary			
Corpus Christi, Texas	33	10	74
United States Steel Corporation[a]			
USS Chemicals, Division			
Clairton, Pennsylvania	150	45	331
Geneva, Utah	13	4	29
Total	6,683	2,000	14,730

[a] These companies produce coal-based rather than petroleum-based benzene.

Table 7-8. GEOGRAPHICAL DISTRIBUTION OF BENZENE PRODUCERS[10, a]

State or territory	Number of companies	Number of plants	Capacity			Percent of total plants	Percent of total capacity
			Gigagrams	Million gallons	Million pounds		
Texas	21	24	2,974	890	6,555	44.44	44.50
Puerto Rico	2	2	986	295	2,173	3.70	14.75
Louisiana	7	6	859	257	1,893	11.11	12.85
Pennsylvania	6	6	444	133	980	11.11	6.65
Virgin Islands	1	1	217	65	479	1.85	3.25
Kentucky	1	1	214	64	471	1.85	3.20
Illinois	2	2	207	62	456	3.70	3.10
Ohio	2	2	174	52	383	3.70	2.60
New Jersey	1	1	117	35	258	1.85	1.75
California	2	2	117	35	257	3.70	1.74
Michigan	1	1	100	30	221	1.85	1.50
Oklahoma	1	1	80	24	177	1.85	1.20
New York	1	1	77	23	169	1.85	1.15
Maryland	1	1	50	15	110	1.85	0.75
Kansas	1	1	43	13	96	1.85	0.65
Utah	1	1	13	4	29	1.85	0.20
Colorado	1	1	10	3	22	1.85	0.15
Totals	52	54	6,682	2,000	14,730		

[a] January 1, 1977.

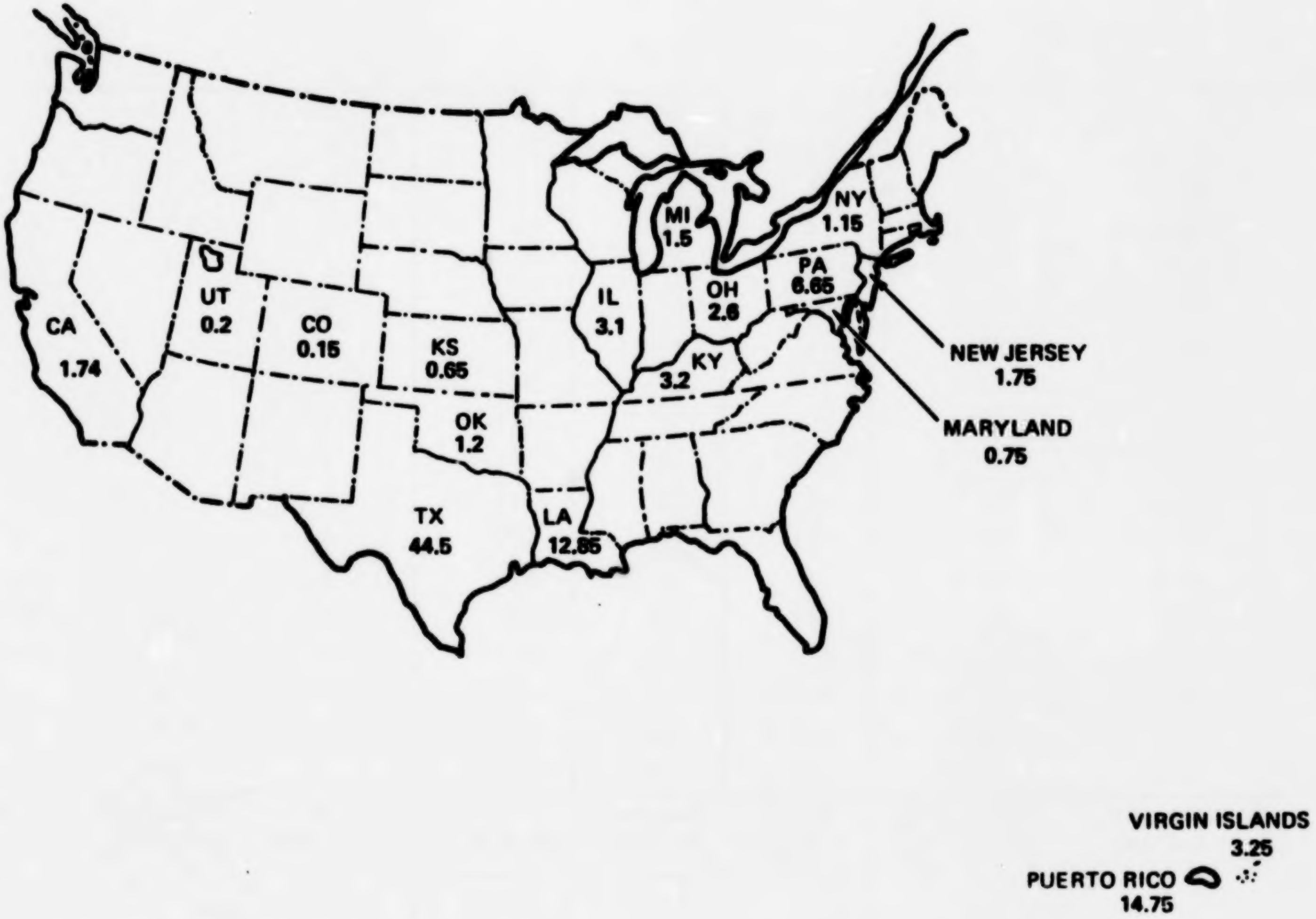
CA
1.74
UT
0.2
CO
0.15
KS
0.65
OK
1.2
TX
44.5
LA
12.85
IL
3.1
MI
1.5
OH
2.6
KY
3.2
PA
6.65
NY
1.15
NEW JERSEY
1.75
MARYLAND
0.75
VIRGIN ISLANDS
3.25
PUERTO RICO
14.75

Figure 7-2. Geographical distribution of benzene producers and percent of total capacity.[10]

Table 7-9. COMPANY SHARES OF TOTAL BENZENE CAPACITY, 1976[10]

(ranked by share)

Company	Number of plants	Capacity			Percent of total capacity
		Gigagrams	Million gallons	Million pounds	
Commonwealth Oil Ref. Co.	1	617	185	1,363	9.25
Shell Oil Co.	3	491	147	1,082	7.35
Gulf Oil Corp.	3	481	144	1,061	7.2
Sun Co., Inc.	4	468	140	1,032	7.0
Exxon Corp.	2	434	130	958	6.5
Phillips Petroleum	2	401	120	884	6.0
American Petrofina, Inc.	3	334	100	736	5.0
Ashland Oil	2	291	87	640	4.35
Atlantic Richfield Co.	3	287	86	633	4.3
Monsanto	1	284	85	626	4.25
Standard Oil Co. (Indiana)	1	284	85	626	4.25
Dow Chemical Co.	2	267	80	589	4.0
Texaco Inc.	2	267	80	589	4.0
Central States Corp.	1	234	70	516	3.5
Union Carbide Corp.	1	234	70	516	3.5
Amerada Hess Corp.	1	217	65	479	3.25
Mobil Corp.	1	200	60	442	3.0
United States Steel Corp.	2	164	49	360	2.45
Cities Service Co.	1	84	25	184	1.25
Crown Central Petro.	1	77	23	169	1.15
Standard Oil of Calif.	1	77	23	169	1.15
Bethlehem Steel	2	63	19	139	0.95
Union Oil Company of Calif.	1	57	17	125	0.85
Kerr-McGee	1	53	16	118	0.8
Pennzoil Co.	1	50	15	110	0.75
Getty Oil Co.	1	43	13	96	0.65
The LTV Corp.	1	33	10	74	0.5
Union Pacific Corp.	1	33	10	74	0.5
Tenneco Inc.	1	33	10	74	0.5
Standard Oil Co. (Ohio)	1	27	8	59	0.4
Marathon Oil Co.	1	23	7	52	0.35
Quintana-Howell	1	23	7	52	0.35
The Charter Co.	1	17	5	37	0.25
Armco Steel Corp.	1	10	3	22	0.15
CF&I Steel Corp.	1	10	3	22	0.15
Independent Refining Corp.	1	10	3	22	0.15
Totals	54	6,680	2,000	14,730	100.0

Table 7-10. RATIO OF MARKET VALUE OF BENZENE PRODUCTION TO TOTAL SALES IN 1976 FOR BENZENE-PRODUCING COMPANIES[11].

Company	Major line of business	Market value of benzene production, 1976[a] (million $)	Total sales 1976[b] (million $)	Value of benzene production as a % of total sales
Amerada Hess Corp.	Petroleum	37.5	3,914.6	1.0
American Petrofina, Inc.	"	57.7	1,070.9	5.4
Armco Steel Corp.	Steel	1.7	3,151.0	.1
Ashland Oil, Inc.	Petroleum	50.2	4,086.9	1.2
Atlantic Richfield Co.	"	50.0	8,462.5	0.6
Bethlehem Steel	Steel	11.0	5,248.0	0.2
CF & I Steel Corp.	"	1.7	413.0	0.4
The Charter Co.	Petroleum	2.9	1,190.9	0.2
Cities Service Co.	"	14.4	3,964.6	0.4
Coastal States Gas Corp.	"	40.4	N.A.	--
Commonwealth Oil Ref. Co.	"	106.8	1,071.4	10.0
Crown Central Pet.	"	13.3	511.7	2.6
Dow Chemical Co.	Chemicals	46.2	5,652.1	0.8
Exxon Corp.	Petroleum	75.1	48,631.0	0.1
Getty Oil Co.	"	7.5	3,058.7	0.2
Gulf Oil Corp.	"	83.2	16,451.0	0.5
Independent Ref. Corp.	"	1.7	N.A.	--
Kerr-McGee Corp.	"	9.2	1,955.1	0.4
The LTV Corp.	Steel	5.8	4,497.0	0.1
Marathon Oil Co.	Petroleum	4.0	3,488.4	0.1
Mobil Corp.	"	34.6	26,063.0	0.1
Monsanto	Chemicals	49.1	4.270.2	1.1
Pennzoil Co.	Petroleum	8.7	1,021.4	0.6
Phillips Pet. Co.	"	106.3	5,697.5	1.2
Quintana-Howell	"	4.0	N.A.	--
Shell Oil Co.	"	85.0	9,230.0	0.9
Standard Oil Co. of Calif.	"	13.3	19,434.0	0.0
Standard Oil Co. (Indiana)	"	49.1	11,532.0	0.4
Standard Oil Co. (Ohio)	"	85.5	2,916.4	2.9
Sun Co., Inc.	"	80.8	5,387.1	1.5
Tenneco Inc.	"	5.8	6,423.4	0.0

(continued)

Table 7-10. Concluded

Company	Major line of business	Market value of benzene production, 1976[a] (million $)	Total sales 1976[b] (million $)	Value of benzene production as a % of total sales
Texaco Inc.	Petroleum	46.2	26,452.0	0.2
Union Carbide Corp.	Chemicals	40.4	6,345.7	0.6
Union Oil Co. of Calif.	Petroleum	9.8	5,350.7	0.2
Union Pacific Corp.	"	5.8	2,024.3	0.3
United States Steel Corp.	Steel	28.3	8,604.2	0.3

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[a] This figure is derived from the following formulas:

Total plant capacity X average percent of capacity at which plants operate multiplied by the average market price per unit of benzene.

Plant capacities given in Table 7-9.

Capacity operating percentage = 75 percent.

Average 1976 unit market price = $0.77/gallon.

[b] NA = Not available.

Table 7-11. MAXIMUM BENZENE REQUIREMENTS OF U. S. PRODUCERS OF ETHYLBENZENE AND STYRENE[9]

Company and location	Maximum benzene requirements of ethylbenzene as of January 1, 1977		
	Gigagrams	Million gallons	Million pounds
American Hoechst Corporation			
Foster Grant, Co., Inc. subsidiary Baton Rouge, Louisiana	400	120	882
Atlantic Richfield Company			
ARCO/Polymers, Inc. subsidiary Port Arthur, Texas	172	52	380
COS-MAR, Inc.			
(joint venture of Borg-Warner Corporation and Cosden Oil & Chemical Co.) Carville, Louisiana	524	157	1,155
The Dow Chemical Company			
Dow Chemical U.S.A. Bay City/Midland, Mich.	190	57	418
Freeport, Texas	595	178	1,311
El Paso Natural Gas Company			
El Paso Products Co. subsidiary Odessa, Texas	95	28	209
Gulf Oil Corporation			
Gulf Oil Chemicals Co. division Petrochemicals Division Welcome (Donaldsonville), Louisiana	212	63	467

(continued)

Table 7-11. Concluded

Company and location	Maximum benzene requirements of ethylbenzene as of January 1, 1977		
	Gigagrams	Million gallons	Million pounds
Monsanto Company			
Monsanto Chemical Intermediates Co. Texas City, Texas	565	169	1,246
Standard Oil Company (Indiana)			
Amoco Chemicals Corp. subsidiary Texas City, Texas	340	102	749
Sun Company, Inc.			
Sun Oil Co. of Pa. subsidiary Sun Petroleum Prod. Co., subsidiary Corpus Christi, Tx.	21	6	47
Union Carbide Corporation			
Chemicals & Plastics, division Seadrift, Texas	117	35	258
TOTAL	3,231	967	7,122

Table 7-12. MAXIMUM BENZENE REQUIREMENTS OF U. S. PRODUCERS OF CUMENE[12]

	Maximum benzene requirements as of January 1, 1977		
Company and location	Gigagrams	Million gallons	Million pounds
Ashland Oil, Inc.			
Ashland Chemical Company division			
Petrochemicals Division Ashland (Cattlettsburg) Kentucky	109	33	241
Clark Oil & Refining Corp.			
Clark Chemical Corp. subsidiary			
Blue Island, Illinois	34	10	76
Costal States Gas Corp.			
Costal States Marketing, Inc. subsidiary			
Corpus Christi, Texas	44	13	97
Getty Oil Company			
Getty Refining & Marketing Company, subsidiary			
El Dorado, Kansas	42	13	93
Gulf Oil Corporation			
Gulf Oil Chemicals Co. division			
Petrochemicals Division			
Philadelphia, Pa.	117	35	259
Port Arthur, Texas	141	42	310
Marathon Oil Company			
Texas City, Texas	66	20	145

Table 7-12. CONCLUDED.

Company and location	Maximum benzene requirements as of January 1, 1977 Gigagrams	Million gallons	Million pounds
Monsanto Company			
Monsanto Chemical Intermediates Co.			
Chocolate Bayou, TX	224	67	493
Standard Oil Company of Calif.			
Chevron Chemical Co. subsidiary			
Petrochemical Division			
Industrial Chemicals			
El Segundo, CA	30	9	69
Standard Oil Co. of Indiana			
Amoco Chemicals Corp. subsidiary			
Texas City, Texas	10	3	21
Sun Company, Inc.			
Sun Oil Company of Pa. subsidiary			
Sun Petroleum Products Co. subsidiary			
Corpus Christi, Texas	78	23	172
Texaco Inc.			
Westville, New Jersey	44	13	97
Union Carbide Corporation			
Union Carbide, Inc. subsidiary			
Penuelas, Puerto Rico	201	60	442
TOTAL CAPACITY	1,139	341	2,515

Table 7-13. MAXIMUM BENZENE REQUIREMENTS OF U. S. PRODUCERS OF CYCLOHEXANE[13]

Company and location	Maximum Benzene Requirements As of January 1, 1977		
	Gigagrams	Million gallons	Million pounds
American Petrofina, Inc.			
Cosden Oil & Chemical Co subsidary			
Big Springs, Texas	33	10	73
Commonwealth Oil Refining Co., Inc.			
Corco Cyclohexane, Inc. subsidiary			
Penuelas, Puerto Rico	110	33	243
Exxon Corporation			
Exxon Chemical Co., division			
Exxon Chemical Co. USA			
Baytown, Texas	137	41	303
Gulf Oil Corporation			
Gulf Oil Chemicals Co., division			
Petrochemicals Division			
Port Arthur, Texas	99	30	219
Phillips Petroleum Company			
Phillips Chemical Company			
Sweeny, Texas	146	44	322
Phillips Puerto Rico Core, Inc., subsidiary			
Guayama, Puerto Rico	198	59	437
Sun Company, Inc.			
Sun Oil Company of Pa. subsidiary			
Sun Petroleum Products Co.			
Tulsa, Oklahoma	77	23	170
Texaco Inc.			
Port Arthur, Texas	110	33	243

(continued)

Table 7-13. Concluded

Company and location	Maximum benzene requirements as of January 1, 1977		
	Gigagrams	Million gallons	Million pounds
Union Oil Company of California			
Beaumont, Texas	83	25	182
Union Pacific Corporation			
Champlin Petroleum Co. subsidiary Corpus Christi, Texas	61	18	134
TOTAL	1,052	316	2,326

the major uses of benzene. The companies are primarily in the petroleum or chemical business. The geographic distribution of the companies is given in Table 7-14 based on their maximum benzene requirements. Consumption of benzene in the manufacture of these products is heavily concentrated in Texas and Louisiana, which combined account for over 80 percent of the benzene product requirements.

Table 7-15 characterizes each firm in terms of its share of the total benzene requirement and its total sales in 1977. The lowest sales for any individual benzene consumer listed is $876 million. The companies requiring the largest amounts of benzene are Monsanto Company, Dow Chemical, and Gulf Oil Company.

7.1.10 Projected Growth Rates

A survey of industry projections indicates that the growth rate of benzene production facilities is in the range of 5 to 5.7 percent per year through 1985.[15,16,17,18] These estimates were made prior to the 1979 oil shortage, however, and it is believed that they are on the high side. Therefore, in the projection of affected facilities in Section 7.1.11, a growth rate of 5 percent was used. This value allows for the replacement of retired tanks.

All announced expansions of benzene production capacity in 1976 were at present production sites, except for three new plants.[9] More recent information indicates that plans for two of the plants have been cancelled.[19,20]

Through 1985, benzene produced via toluene dealkylation is expected to decrease by 4 percent per year and benzene produced in ethylene plants is expected to increase by 8.5 percent per year.[21] Benzene made via refinery reformate is expected to grow by only 2 percent per year.[21]

Between 1980 and 1990, the amount of benzene used in ethylbenzene is expected to increase by about 4.5 percent per year.[22] During the same period, the amount of benzene used in cyclohexane increased by about 5 percent.[22]

7.1.11 Benzene Storage Facility Growth Estimates

Based on an industry survey, there are 143 facilities with benzene storage tanks in the United States. These facilities include 28 large producers, 34 small producers, 77 consumers, and 4 bulk storage terminals (see Section 3.3.2 for a definition of large and small producers).

Table 7-14. GEOGRAPHICAL DISTRIBUTION OF BENZENE CONSUMERS[9,12,13]

Product and location	Number of companies	Number of plants	Maximum benzene requirement[a] Gigagrams	Million gallons	Million pounds	Percent of total max. benzene requirement
Ethylbenzene and styrene						
Texas	7	7	1,904	570	4,200	59.0
Louisiana	3	3	1,136	340	2,504	35.1
Michigan	1	1	190	57	418	5.9
			3,230	967	7,122	
Cyclohexane						
Texas	7	7	778	233	1,719	73.9
Puerto Rico	2	2	197	59	437	18.8
Oklahoma	1	1	77	23	170	7.3
			1,052	315	2,326	
Cumene						
Texas	6	6	561	168	1,238	49.2
Puerto Rico	1	1	200	60	442	17.6
Pennsylvania	1	1	117	35	259	10.3
Kentucky	1	1	110	33	241	9.6
New Jersey	1	1	43	13	97	3.9
Kansas	1	1	43	13	93	3.7
Illinois	1	1	33	10	76	3.0
California	1	1	30	9	69	2.7
			1,139	341	2,515	

[a] Totals may disagree due to rounding.

Table 7-15. TOTAL BENZENE REQUIREMENT AND 1977 ANNUAL SALES OF BENZENE-CONSUMING COMPANIES[9,12,13,14]

Benzene consumer	Maximum benzene requirement		Percent total benzene requirement[a]	Sales, 1977 unless otherwise indicated[b]
	Gigagrams	million gallons		(million dollars)
American Hoechst	400	120	7.4	11,287.4
American Petrofina	33	10	0.6	1,076.4
Ashland Oil, Inc.	109	33	2.0	54,262.0 (YE 9/78)
Atlantic Richfield Co.	172	52	3.2	10,969.0
COS-MAR, Inc.	524	157	9.7	--------
(joint venture Borg Warner Corp.				2,031.9
and Cosden Oil & Chemical Co.)				NA
Clark Oil & Refining Company	34	10	0.6	876.0
Coastal States Gas Corporation	44	13	0.8	3,452.6
Commonwealth Oil Refining Co., Inc.	110	33	2.0	930.5
The Dow Chemical Co.	785	235	14.5	6,234.3
El Paso Natural Gas Company	95	28	1.7	1,694.7
Exxon Corporation	137	41	2.5	54,126.0
Getty Oil Company	42	13	0.8	3,320.0
Gulf Oil Corporation	569	170	10.5	17,840.0
Marathon Oil Company	66	20	1.2	4,252.0
Monsanto Company	789	236	14.5	4,594.5
Phillips Petroleum Co.	344	103	6.3	6,284.2
Standard Oil Co. (Indiana)	350	105	6.4	13,020.0
Standard Oil of California	30	9	0.6	20,917.0
Sun Company, Inc.	176	52	3.3	--------
(subsidiary of Sun Oil of Pennsylvania)				6,418.1

(continued)

Table 7-15. Concluded

Benzene consumer	Maximum benzene requirement		Percent total benzene requirement[a]	Sales, 1977 unless otherwise indicated[b]
	Gigagrams	million gallons		(million dollars)
Texaco, Inc.	154	46	2.8	27,920.0
Union Carbide Corp.	318	95	5.9	7,036.1
Union Oil of CA.	83	25	1.5	5,668.5
Union Pacific Corp.	61	18	1.1	2,024.3

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[a] 100 percent benzene requirement for ethylbenzene and styrene, cyclohexane, and cumene = 5,425 Gg (1,624 million gallons).

[b] Companies whose sales are unavailable do not have a 10-K on file with the Security Exchange Commission and are assumed to be privately held. It is likely that their sales figures are lower than those of publicly held companies. NA = Not available and YE = Year ended.

In Section 6.2.2, a 5 percent growth rate (see Section 7.1.10) was applied to the 1979 baseline number of facilities to estimate the number of facilities in 1980, 1985, and 1990. The results of these calculations are shown in Table 6-5.

7.2 COST ANALYSIS OF CONTROL OPTIONS FOR BENZENE STORAGE TANKS

This section presents estimates of the capital cost, annualized cost, and cost effectiveness developed by applying each of the control options in Tables 5-1 and 5-2 to each new and existing model plant in Table 5-5. The capital cost, which represents the initial investment for control equipment and its installation by the owner or operator of a facility, was developed using vendor quotes, EPA reports, and the K.M. Guthrie method of estimating capital cost.[23] The capital cost was then annualized by using a capital recovery factor of 13.15 or 16.27 (see Section 7.2.1.2), which was based on equipment life and the interest rate on the capital. The total annualized cost attributable to the control equipment was estimated by adding the annual costs for maintenance and inspections, if necessary, and the annual taxes to the annualized capital cost. The net annualized cost was estimated by subtracting the value of the annual amount of benzene saved (a solvent credit of $0.34/liter) from the total annualized cost. The cost effectiveness of applying a particular control option to a model plant was determined by dividing the net annualized cost by the emissions reduction of the control option with respect to the baseline emissions. The cost effectiveness permits a comparison of each option on an equal basis with the baseline. The marginal cost effectiveness, which can be used to evaluate an option relative to the preceeding option, was also determined. The marginal cost effectiveness was estimated by dividing the difference in the net annualized costs between two options by the difference in the emissions reductions between those options.

7.2.1 Existing Facilities

7.2.1.1 Capital costs. The capital costs for the control options not requiring the use of a vapor control system were based on cost estimates obtained from vendors and the Control Techniques Guideline (CTG) for external floating-roof tanks.[24] Vendors were contacted and asked to provide estimates of the costs to install fixed or internal floating roofs on existing storage tanks (Tables 7-16, 7-17, 7-18, and 7-19). The external floating-roof tank CTG was the source of the costs for cleaning, degassing, and certifying modified tanks and installing secondary seals on external floating roofs (Table 7-20). The secondary seal costs were also used to evaluate the costs of retrofitting internal floating roofs with secondary seals.

Because the costs for modifying existing storage tanks were obtained for a range of five tank sizes, the cost of modifying each tank in a model facility was estimated by performing a straight line linear regression analysis on the five paired functions of cost and tank size. These five paired functions included: (1) the cost of fitting a roof on an external floating-roof tank versus the square of the tank diameter, (2) the cost of installing a secondary seal on an internal or external floating roof versus the tank diameter, (3) the cost of cleaning, degassing, and certifying a tank versus tank volume, (4) the cost of removing a noncontact internal floating roof versus the square of the tank diameter, and (5) the cost of installing a contact or noncontact internal floating roof versus the square of the tank diameter.

The capital costs of installing a carbon adsorption or thermal oxidation vapor control system to reduce benzene emissions from an existing model facility are presented in Tables 7-21 and 7-22, respectively. These costs were estimated from information supplied by vendors of the control equipment. It was assumed that each system, which was sized to recover the emissions from a tank being filled by a barge at a rate of 7,750 liters/minute (2,000 gallons/minute), was connected to all benzene storage tanks at a facility.[29] Approximately 180 meters (600 feet) of vapor collection pipe was used to connect each tank to the carbon adsorption or thermal oxidation unit. The carbon adsorption and thermal oxidation systems also utilized pressure switches and blowers (see Section 4.2.8). Water seals were used to reduce the danger of flashback, and it was assumed that an adequate supply of steam was available for regenerating the carbon bed if a carbon adsorption unit were used.

Also included in the capital costs for a carbon adsorption and a thermal oxidation system was the cost for safety devices, including a

Table 7-16. COST OF INSTALLING A NONCONTACT INTERNAL FLOATING ROOF IN AN EXISTING FIXED-ROOF TANK[a]

Tank dimensions[b] (meters)	Installed capital cost of an aluminum noncontact internal floating roof[c,25]	Cost of cleaning, degassing, and certification[24]	Total cost
8 x 12	$ 6,600	$1,300	$7,900
13 x 15	10,550	2,000	12,500
14 x 17	11,750	2,500	14,250
21 x 12	18,350	3,400	21,750
27 x 15	25,450	6,150	31,600

[a] Costs are in first-quarter 1979 dollars.

[b] Diameter by height

[c] Gulf Coast installation.

Table 7-17. COST OF INSTALLING A CONTACT INTERNAL FLOATING ROOF IN AN EXISTING FIXED-ROOF TANK[a]

Tank dimensions[b] (meters)	Installed capital cost of an aluminum contact internal floating roof[c,26]	Cost of cleaning, degassing, and certification[24]	Total cost
8 x 12	$ 9,300	$1,300	$10,600
13 x 15	15,300	2,000	17,300
14 x 17	17,500	2,500	20,050
21 x 12	32,400	3,400	35,800
27 x 15	48,950	6,150	55,100

[a] Costs are in first-quarter 1979 dollars.

[b] Diameter by height.

[c] Gulf Coast installation.

Table 7-18. COST OF INSTALLING A FIXED ROOF ON AN EXISTING EXTERNAL FLOATING-ROOF TANK[a]

Tank diameter (meters)	Installed capital cost of aluminum dome[b,c,27]	Cost of cleaning, degassing, and certification[24]	Total cost
8 x 12	$ 7,600	$1,300	$ 8,900
13 x 15	13,800	2,000	15,800
14 x 17	15,800	2,500	18,300
21 x 12	32,600	3,400	36,000
27 x 15	50,100	6,150	56,300

[a] Costs are in first-quarter 1979 dollars.

[b] Gulf Coast installation.

[c] Self-supporting aluminum dome costs include removal of platform and ladder as well as addition of new rim angle.

Table 7-19. COST OF INSTALLING A CONTACT INTERNAL FLOATING ROOF IN AN EXISTING NONCONTACT INTERNAL FLOATING-ROOF TANK[a]

Tank dimensions[b] (meters)	Installed capital cost of an aluminum contact internal floating roof[c,26]	Cost of cleaning, degassing, and certification[24]	Cost of removing noncontact internal floating roof[28]	Total cost
8 x 12	$ 9,300	$1,300	$ 600	$11,200
13 x 15	15,300	2,000	1,000	18,300
14 x 17	17,500	2,500	1,100	21,200
21 x 12	32,400	3,400	2,000	37,800
27 x 15	48,950	6,150	2,700	57,800

[a] Costs are in first-quarter 1979 dollars.

[b] Diameter by height.

[c] Gulf Coast installation.

Table 7-20. COST OF INSTALLING A SECONDARY SEAL ON AN EXISTING INTERNAL OR EXTERNAL FLOATING ROOF[a]

Tank dimensions[b] (meters)	Installed capital cost of secondary seal[24]	Cost of cleaning, degassing, and certification[24]	Total cost
8 x 12	$ 3,810	$1,300	$ 5,100
13 x 15	5,520	2,000	7,520
14 x 17	6,400	2,500	8,900
21 x 12	8,690	3,400	12,090
27 x 15	10,500	6,150	16,650

[a] Costs are in first-quarter 1979 dollars.

[b] Diameter by height.

Table 7-21. COST OF INSTALLING A CARBON ADSORPTION SYSTEM AT AN EXISTING MODEL FACILITY[a]

Carbon adsorption system components	Large benzene producer	Small benzene producer	Benzene consumer or bulk storage terminal
Piping, pressure switches, and backup pressure switches	$67,840	$43,630	$27,490
Two water seals and two backup water seals	12,480	12,480	12,480
Two blowers and two backup blowers	14,560	14,560	14,560
Benzene saturator and related equipment	62,140	62,140	62,140
Carbon adsorption unit and related equipment	109,060	109,060	109,060
Cleaning and degassing of tanks	18,000	8,400	4,800
Total	$284,080	$250,270	$230,530

[a] Costs are in first-quarter 1979 dollars.

Table 7-22. COST OF INSTALLING A THERMAL OXIDATION SYSTEM AT AN EXISTING MODEL FACILITY[a]

Thermal oxidation system components	Large benzene producer	Small benzene producer	Benzene consumer or bulk storage terminal
Piping, pressure switches and backup pressure switches	$67,840	$43,630	$27,490
Two water seals and two backup water seals	12,480	12,480	12,480
Two blowers and two backup blowers	14,560	14,560	14,560
Benzene saturator and related equipment	62,140	62,140	62,140
Thermal oxidation unit and related equipment	67,020	67,020	67,020
Cleaning and degassing of tanks	18,000	8,400	4,800
Total	$242,040	$208,230	$188,490

[a] Costs are in first-quarter 1979 dollars.

benzene saturator and redundant pressure switches, water seals, and blowers.

The capital cost required for each existing model facility to comply with the requirements of each control option is shown in Table 7-23.

7.2.1.2 Annualized costs. The capital cost for each control option was annualized using a useful lifetime of 10 years for internal and external floating roofs and seals.[30] All other hardware including fixed roofs, carbon adsorption systems, and thermal oxidation systems was assumed to have a useful lifetime of 15 years. No salvage value was used in estimating the annualized cost for any option.

Using a 10 percent interest rate in conjunction with these useful lifetimes, the capital recovery rates are 16.27 percent and 13.15 percent for 10 years and 15 years, respectively. With the addition of a 4 percent rate for taxes, insurance, and administrative expenses, the capital recovery rates become 20.27 percent and 17.15 percent, respectively.

A yearly maintenance charge of 5 percent of the installed capital cost was added when converting a fixed-roof tank to an internal floating-roof tank. No charge was assessed when converting an external floating-roof tank to an internal floating-roof tank. A yearly maintenance charge of 1 percent of the installed capital cost was included in the costs for the options requiring the use of a vapor control system.

When retrofitting a fixed-roof tank with an internal floating roof, it was assumed that the tank owner or operator would conduct biannual visual inspections of the internal floating roof through roof hatches on the fixed roof. These inspections were estimated to cost $200 annually. It was also assumed that an additional and more thorough inspection inside each tank would be conducted at least once every 5 years at an estimated cost of $1,000, including the costs for cleaning and degassing the tank. This 5-year inspection was projected to have an annualized cost of approximately $200. Owners or operators of all tanks other than fixed-roof tanks were assumed to already have similar inspection schedules.[31]

For the control options requiring the use of vapor control systems, utility expenses were estimated using electricity costs of $0.04/kWh, natural gas costs of $0.07/m^3, and steam costs of $7.23/Mg. It was also

Table 7-23. CAPITAL COSTS FOR EXISTING MODEL PLANTS[a]

Tank dimensions[b] [meters x meters (ft x ft)]	Option[c]					
	I	II	III	IV	V(A)	V(B)
Large benzene producer						
12 x 9 (40 x 30)	0	0	$17,000	$22,500		
18 x 12 (60 x 39.8)	0	10,400	28,200	35,800		
8 x 5 (25 x 18)	0	0	0	5,000		
9 x 9 (30 x 30)	0	0	0	5,700		
13 x 13 (42 x 41.8)	0	0	18,200	23,900		
24 x 9 (80 x 30)	0	0	45,800	55,400		
27 x 15 (90 x 48)	0	0	58,000	68,600		
Total	0	10,400	167,200	216,900	284,080	242,040
Small benzene producer						
3 x 11 (10 x 36)	7,000-7,400[d]	7,000-7,400[d]	7,400	9,900		
13 x 13 (42 x 41.8)	0	0	18,200	23,900		
8 x 11 (25 x 35.9)	0	0	11,200	15,200		
32 x 7 (104 x 24)	0	0	0	16,500		
Total	7,000-7,400	7,000-7,400	36,800	65,500	250,270	208,230
Benzene consumer						
12 x 11 (40 x 35.9)	0	0	17,100	22,600		
18 x 15 (60 x 48)	0	0	0	10,800		
Total	0	0	17,100	33,400	230,530	188,490
Bulk storage terminal						
12 x 11 (40 x 35.9)	0	0	17,100	22,600		
18 x 15 (60 x 48)	0	0	0	10,800		
Total	0	0	17,100	33,400	230,530	188,490

[a] Costs in first quarter 1979 dollars.

[b] Diameter x height.

[c] Control options from Table 5-1.

[d] Cost for noncontact and contact internal floating roofs, respectively.

assumed that one person-year of operating labor, at $8.00/hr for 2,000 hours/year, would be required to operate and maintain a vapor control system. Annual emission monitoring costs were also included in the annualized costs for operating a vapor control system. These annualized monitoring costs were estimated using a capital cost of $2,900 for a flame ionization hydrocarbon detector, a capital cost of $1,000 for a flow measurement device, and an annual cost of $1,700 for bottled gas to operate the flame ionization detector. All these monitoring costs were annualized for a total charge of $2,500/year.

The annualized cost of applying each of the control options to each existing model facility is shown in Table 7-24.

7.2.1.3 Cost effectiveness. The cost effectiveness and net annualized cost of applying each of the control options to each of the model plants are shown in Tables 7-25 through 7-27. The cost effectiveness of each option and its impact on each model plant are illustrated graphically in Figure 7-3.

Option I, which would require that each fixed-roof tank be retrofitted with an internal floating roof, has a cost effectiveness ranging from $0/Mg emission reduction for the large benzene producer, benzene consumer, and bulk storage terminal to greater than $1,900/Mg emission reduction for the small benzene producer. The cost effectiveness for Option II, which would require that each fixed-roof tank be retrofitted with an internal floating roof and each external floating-roof tank be retrofitted with a secondary seal, ranges from $0/Mg emission reduction for the benzene consumer and bulk storage terminal to greater than $1,900/Mg emission reduction for the small benzene producer. Option III, which would require that each tank be converted to a contact internal floating-roof tank with a liquid-mounted primary seal, has a cost effectiveness ranging from $680/Mg emission reduction for the large benzene producer to $850/Mg emission reduction for the small benzene producer. Option IV, which would require that each tank be converted to a contact internal floating-roof tank with a liquid-mounted primary seal and a continuous secondary seal, has a cost effectiveness ranging from $800/Mg emission reduction for the large benzene producer to $1,200/Mg emission reduction

Table 7-24. ANNUALIZED COSTS FOR EXISTING MODEL PLANTS

Parameter	Option[a]					
	I	II	III	IV	V(A)	V(B)
Large benzene producer						
Capital recovery charge[b]	NA	$2,100	$33,100	$43,200	$48,700	$41,500
Maintenance cost[c]	NA	NA	NA	NA	2,800	2,400
Inspection fee[d]	NA	NA	NA	NA	NA	NA
Utilities cost[e]	NA	NA	NA	NA	11,600	9,400
Operating labor cost	NA	NA	NA	NA	16,000	16,000
Emission monitoring cost	NA	NA	NA	NA	2,500	2,500
Total Annualized Cost	NA	2,100	33,100	43,200	81,600	71,800
Small benzene producer						
Capital recovery charge[b]	1,400-1,500	1,400-1,500	7,500	13,300	42,900	35,700
Maintenance cost[c]	400-400	400-400	400	500	2,500	2,100
Inspection fee[d]	400-400	400-400	400	400	NA	NA
Utilities cost[e]	NA	NA	NA	NA	11,600	9,400
Operating labor cost	NA	NA	NA	NA	16,000	16,000
Emission monitoring cost	NA	NA	NA	NA	2,500	2,500
Total Annualized Cost	2,200-2,300	2,200-2,300	8,300	14,200	75,500	65,700
Benzene consumer						
Capital recovery charge[b]	NA	NA	3,500	6,800	39,500	32,300
Maintenance cost[c]	NA	NA	NA	NA	2,300	1,900
Inspection fee[d]	NA	NA	NA	NA	NA	NA
Utilities cost[e]	NA	NA	NA	NA	11,600	9,400
Operating labor cost	NA	NA	NA	NA	16,000	16,000
Emission monitoring cost	NA	NA	NA	NA	2,500	2,500
Total Annualized Cost	NA	NA	3,500	6,800	71,900	62,100

(continued)

Table 7-24. Concluded

Parameter	Option[a]					
	I	II	III	IV	V(A)	V(B)
Bulk storage terminal						
Capital recovery charge[b]	NA	NA	3,500	6,800	39,500	32,300
Maintenance cost[c]	NA	NA	NA	NA	2,300	1,900
Inspection fee[d]	NA	NA	NA	NA	NA	NA
Utilities cost[e]	NA	NA	NA	NA	11,600	9,400
Operating labor cost	NA	NA	NA	NA	16,000	16,000
Emission monitoring cost	NA	NA	NA	NA	2,500	2,500
Total Annualized Cost	NA	NA	3,500	6,800	71,900	62,100

[a] NA = Not applicable.

[b] Total capital cost obtained from Table 7-23. The capital recovery factor is 20.27 percent for internal and external floating roofs and seals, and 17.15 percent for all other hardware.

[c] Determined as 5 percent of total capital costs for Options I, II, III, IV, and as 1 percent of total capital costs for Options V(A) and V(B).

[d] Inspection fee includes charges of $200 for visual inspections twice per year and $200 a year for a 5-year thorough inspection of seals (including cleaning and degassing costs) for both noncontact and contact internal floating roofs.

[e] Utilities cost consists of steam and electrical requirements for Option V(A) and natural gas and electrical requirements for Option V(B).

Table 7-25. COSTS FOR EXISTING LARGE BENZENE PRODUCER

Parameters	Option					
	I	II	III	IV	V(A)	V(B)
Capital cost ($)	0	10,400	167,200	216,900	284,100	242,000
Annualized cost (less solvent credit, $)	0	2,100	33,100	43,200	81,600	71,800
Emission reduction from baseline (Mg/yr)	0	8	31	36.3	34.9	37.2
Solvent credit ($)	0	3,100	12,100	14,100	13,600	0
Net annualized cost ($)	0	(1,000)[b]	21,000	29,100	68,000	71,800
Cost effectiveness ($/Mg emission reduction)	0	120	680	800	1,900	1,900
Marginal cost effectiveness ($/Mg emission reduction)	0	120	960	1,500	NA[a]	47,000

[a] Not applicable.

[b] Credit is indicated by parenthesis.

Table 7-26. COSTS FOR EXISTING SMALL BENZENE PRODUCER

Parameters	Option					
	I	II	III	IV	V(A)	V(B)
Capital cost ($)	7,000-7,400[a]	7,000-7,400[a]	36,800	65,500	250,300	208,200
Annualized cost (less solvent credit, $)	2,200-2,300[a]	2,200-2,300[a]	8,300	14,200	75,500	65,700
Emission reduction from baseline (Mg/yr)	0-1	0-1	6.7	9.1	10.8	11.3
Solvent credit ($)	0-400[b]	0-400[b]	2,600	3,500	4,200	0
Net annualized cost ($)	2,200-1,900[a]	2,200-1,900[a]	5,700	10,700	71,300	65,700
Cost effectiveness ($/Mg emission reduction)	>1,900	>1,900	850	1,200	6,600	5,800
Marginal cost effectiveness ($/Mg)	0	0	520-670	2,100	36,000	25,000

[a] Range of costs for option which allows the use of noncontact and contact internal floating roofs, respectively, in affected tanks.

[b] Range of credit for option which allows the use of noncontact and contact internal floating roofs, respectively, in affected tanks.

Table 7-27. COSTS FOR EXISTING BENZENE CONSUMER OR BULK STORAGE TERMINAL

Parameters	Option					
	I	II	III	IV	V(A)	V(B)
Capital cost ($)	0	0	17,100	33,400	230,500	188,500
Annualized cost (less solvent credit, $)	0	0	3,500	6,800	71,900	62,100
Emission reduction from baseline (Mg/yr)	0	0	3.2	4.5	5.4	5.67
Solvent credit ($)	0	0	1,200	1,800	2,100	0
Net annualized cost ($)	0	0	2,300	5,000	69,800	62,100
Cost effectiveness ($/Mg emission reduction)	0	0	720	1,100	13,000	11,000
Marginal cost effectiveness ($/Mg emission reduction)	0	0	720	2,100	72,000	49,000

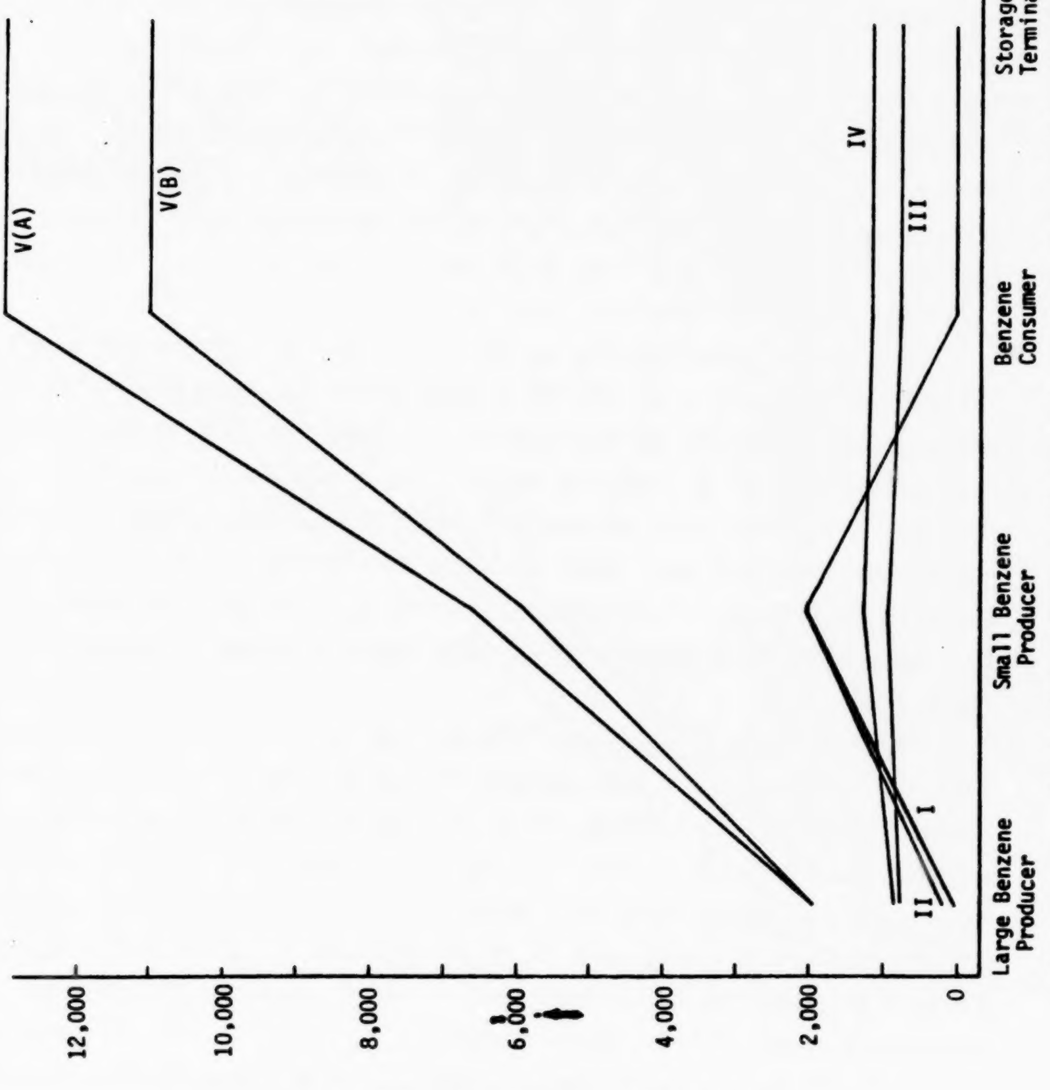

Figure 7-3. Cost effectiveness of control options for existing facilities.

for the small benzene producer. The cost effectiveness for Option V, which would require that each tank be fittd to a vapor control system, is much larger, ranging from $1,900/Mg emission reduction for the large benzene producer to $13,000/Mg emission reduction for the benzene consumer and bulk storage terminal.

7.2.2 New Facilities

7.2.2.1 Capital costs. The installed capital costs used in the cost analysis for existing facilities were also used in the analysis for new facilities. The capital costs for installing floating roofs in new tanks are identical with those costs presented in Tables 7-16 through 7-20 minus the costs of cleaning, degassing, and certification. Similarly, the capital costs for installing carbon adsorption and thermal oxidation systems at new facilities are identical to those costs for existing facilities presented in Tables 7-21 and 7-22, respectively, minus the cleaning, degassing, and certification costs.

In order to determine the capital cost for each of the new model facilities to comply with Options I through III in Table 5-2, a regression analysis was performed on the five paired functions of cost and tank size (see Section 7.2.1.1). Options IV(A) (carbon adsorption) and IV(B) (thermal oxidation) were evaluated using the same methodology, information, and assumptions that were used in evaluating Options V(A) and V(B) for existing facilities. The capital cost required for each new model facility to comply with the requirements of each control option is shown in Table 7-28.

7.2.2.2 Annualized costs. The capital cost for each new model facility to comply with each control option was annualized using the same useful lifetimes and interest rates that were used to estimate the annualized cost for each existing model facility. Consequently, the capital recovery rates used for annualizing the capital costs of equipment with lifetimes of 10 years and 15 years were 20.27 percent and 17.15 percent, respectively. Table 7-29 shows the annualized cost for each new model facility to comply with each of the control options.

7.2.2.3 Cost effectiveness. The cost effectiveness and net annualized cost of applying each of the control options to each of the model plants are shown in Tables 7-30 through 7-32. The cost effectiveness of each

Table 7-28. CAPITAL COSTS FOR NEW MODEL PLANTS[a]

Tank dimensions[b] [meters x meters (ft x ft)]	Option[c] I	II	III	IV(A)	IV(B)
Large benzene producer					
12 x 9 (40 x 30)	0	$ 4,700	$10,200		
18 x 12 (60 x 39.8)	0	25,400	25,400		
8 x 5 (25 x 18)	0	1,900	5,900		
9 x 9 (30 x 30)	0	2,700	7,200		
13 x 13 (42 x 41.8)	0	5,100	10,800		
24 x 9 (80 x 30)	0	18,400	28,000		
27 x 15 (90 x 48)	0	23,300	33,900		
Total	0	81,500	121,400	266,080	224,040
Small benzene producer					
3 x 11 (10 x 36)	6,100-6,500[d]	6,500	9,000		
13 x 13 (42 x 41.8)	0	5,100	10,800		
8 x 11 (25 x 35.9)	0	1,900	5,900		
32 x 7 (104 x 24)	0	31,100	43,200		
Total	6,100-6,500	44,600	68,900	241,870	199,830
Benzene consumer					
12 x 11 (40 x 35.9)	0	4,700	10,200		
18 x 15 (60 x 48)	0	10,400	18,000		
Total	0	15,100	28,200	225,730	183,690
Bulk storage terminal					
12 x 11 (40 x 35.9)	0	4,700	10,200		
18 x 15 (60 x 48)	0	10,400	18,000		
Total	0	15,100	28,200	225,730	183,690

[a] Costs in first quarter 1979 dollars.

[b] Diameter x height.

[c] Control options from Table 5-2.

[d] Cost for noncontact and contact internal floating roofs, respectively.

Table 7-29. ANNUALIZED COSTS FOR NEW MODEL PLANTS

Parameter	Option[a]				
	I	II	III	IV(A)	IV(B)
Large benzene producer					
Capital recovery charge[b]	NA	$15,700	$23,800	$45,600	$38,400
Maintenance cost[c]	NA	NA	NA	2,700	2,200
Inspection fee[d]	NA	NA	NA	NA	NA
Utilities cost[e]	NA	NA	NA	11,600	9,400
Operating labor cost	NA	NA	NA	16,000	16,000
Emission monitoring cost	NA	NA	NA	2,500	2,500
Total annualized cost	NA	15,700	23,800	78,400	68,500
Small benzene producer					
Capital recovery charge[b]	1,200-1,300	9,000	14,000	41,500	34,300
Maintenance cost[c]	300-300	300	400	2,400	2,000
Inspection fee[d]	400-400	400	400	NA	NA
Utilities cost[e]	NA	NA	NA	11,600	9,400
Operating labor cost	NA	NA	NA	16,000	16,000
Emission monitoring cost	NA	NA	NA	2,500	2,500
Total annualized cost	1,900-2,000	9,700	14,800	74,000	64,200
Benzene consumer					
Capital recovery charge[b]	NA	3,100	5,700	38,700	31,500
Maintenance cost[c]	NA	NA	NA	2,300	1,800
Inspection fee[d]	NA	NA	NA	NA	NA
Utilities cost[e]	NA	NA	NA	11,600	9,400
Operating labor cost	NA	NA	NA	16,000	16,000
Emission monitoring cost	NA	NA	NA	2,500	2,500
Total annualized cost	NA	3,100	5,700	71,100	61,200

(continued)

Table 7-29. Concluded

Parameter	Option[a]				
	I	II	III	IV(A)	IV(B)
Bulk storage terminal					
Capital recovery charge[b]	NA	3,100	5,700	38,700	31,500
Maintenance cost[c]	NA	NA	NA	2,300	1,800
Inspection fee[d]	NA	NA	NA	NA	NA
Utilities cost[e]	NA	NA	NA	11,600	9,400
Operating labor cost	NA	NA	NA	16,000	16,000
Emission monitoring cost	NA	NA	NA	2,500	2,500
Total annualized cost	NA	3,100	5,700	71,100	61,200

[a] NA = not applicable.

[b] Total capital costs obtained from Table 7-28. The capital recovery rate is 20.27 percent for an internal floating roof and 17.15 for all other hardware.

[c] Determined as 5 percent of total capital cost for Options I, II, and III, and as 1 percent of total capital costs for Options IV(A) and IV(B).

[d] Inspection fee includes charges of $200 for visual inspection twice per year and $200 per year for a 5-year thorough inspection of seals (including cleaning and degassing costs) for both noncontact and contact internal floating roofs.

[e] Utilities costs consists of steam and electrical requirements for Option IV(A) and natural gas and electrical requirements for Option IV(B).

Table 7-30. COSTS FOR NEW LARGE BENZENE PRODUCER

Parameters	Option[a]				
	I	II	III	IV(A)	IV(B)
Capital cost ($)	0	81,500	121,400	266,100	224,000
Annualized cost (less solvent credit, $)	0	15,700	23,800	78,400	68,500
Emission reduction from baseline (Mg/yr)	0	27	32.3	30.9	33.2
Solvent credit ($)	0	10,500	12,600	12,000	0
Net annualized cost ($)	0	5,200	11,200	66,400	68,500
Cost effectiveness ($/Mg emission reduction)	0	190	350	2,100	2,100
Marginal cost effectiveness ($/Mg emission reduction)	0	190	1,100	NA	64,000

[a] NA = not applicable.

Table 7-31. COSTS FOR NEW SMALL BENZENE PRODUCER

Parameters	Option[a]				
	I[a]	II	III	IV(A)	IV(B)
Capital cost ($)	6,100-6,500	44,600	68,900	241,900	199,800
Annualized cost (less solvent credit, $)	1,900-2,000	9,700	14,800	74,000	64,200
Emission reduction from baseline (mg/yr)	0-1	14.7	17.1	18.8	19.3
Solvent credit ($)	0-400	5,700	6,700	7,300	0
Net annualized cost ($)	1,900-1,600	4,000	8,100	66,700	64,200
Cost effectiveness ($/Mg emission reduction)	1,900-1,600	270	470	3,500	3,300
Marginal cost effectiveness ($/Mg emission reduction)	0	140-180	1,700	34,000	26,000

[a] Range of costs, credit, and cost effectiveness for Option I which allows the use of noncontact and contact internal floating roofs, respectively, in affected tanks.

Table 7-32. COSTS FOR NEW BENZENE CONSUMER OR BULK STORAGE TERMINAL

Parameters	Option				
	I	II	III	IV(A)	IV(B)
Capital cost ($)	0	15,100	28,200	225,700	183,700
Annualized cost (less solvent credit, $)	0	3,100	5,700	71,100	61,200
Emission reduction from baseline (Mg/yr)	0	7.7	9.0	9.9	10.17
Solvent credit ($)	0	3,000	3,500	3,900	0
Net annualized cost ($)	0	100	2,200	67,200	61,200
Cost effectiveness ($/Mg emission reduction)	0	13	240	6,800	6,000
Marginal cost effectiveness ($/Mg emission reduction)	0	13	1,600	72,000	50,000

option and its impact on each model plant are illustrated graphically in Figure 7-4.

Option I, whch would require that each fixed-roof tank have an internal floating roof, has a cost effectiveness ranging from \$0/Mg emission reduction for the large benzene producer, benzene consumer, and bulk storage terminal to \$1,900/Mg emission reduction for the small benzene producer. The cost effectiveness for Option II, which would require that each new tank have a contact internal floating roof with a liquid-mounted primary seal, ranges from \$13/Mg emission reduction for the benzene consumer and bulk storage terminal to \$270/Mg emission reduction for the small benzene producer. Option III, which would require that each tank have a contact internal floating roof with a liquid-mounted primary seal and a continuous secondary seal, has a cost effectiveness ranging from \$240/Mg emission reduction for the benzene consumer and bulk storage terminal to \$470/Mg emission reduction for the small benzene producer. The cost effectiveness of Option IV, which would require that each tank be fitted to a vapor control system, is much larger, ranging from \$2,100/Mg emission reduction for the large benzene producer to \$6,800/Mg emission reduction for the benzene consumer and bulk storage terminal.

Table 7-33 summarizes the costs and cost effectiveness of the control options on a nationwide basis. This information is presented for both existing and new benzene storage tanks. Table 7-33 also facilitates an assessment of the potential effect of each control option.

7.3 OTHER COST CONSIDERATIONS

This section discusses the additional costs incurred by facilities that are complying with Occupational Safety and Health Administration (OSHA) requirements and other EPA air pollution regulations.

7.3.1 Costs Associated with OSHA Compliance

No additional costs are required for complying with OSHA regulations because the affected facilities are expected to already be in compliance with these regulations.

7.3.2 Costs Associated with Other EPA Air Pollution Regulations

There are three proposed EPA regulations that would impact many of the same facilities affected by a regulation for benzene storage tanks.

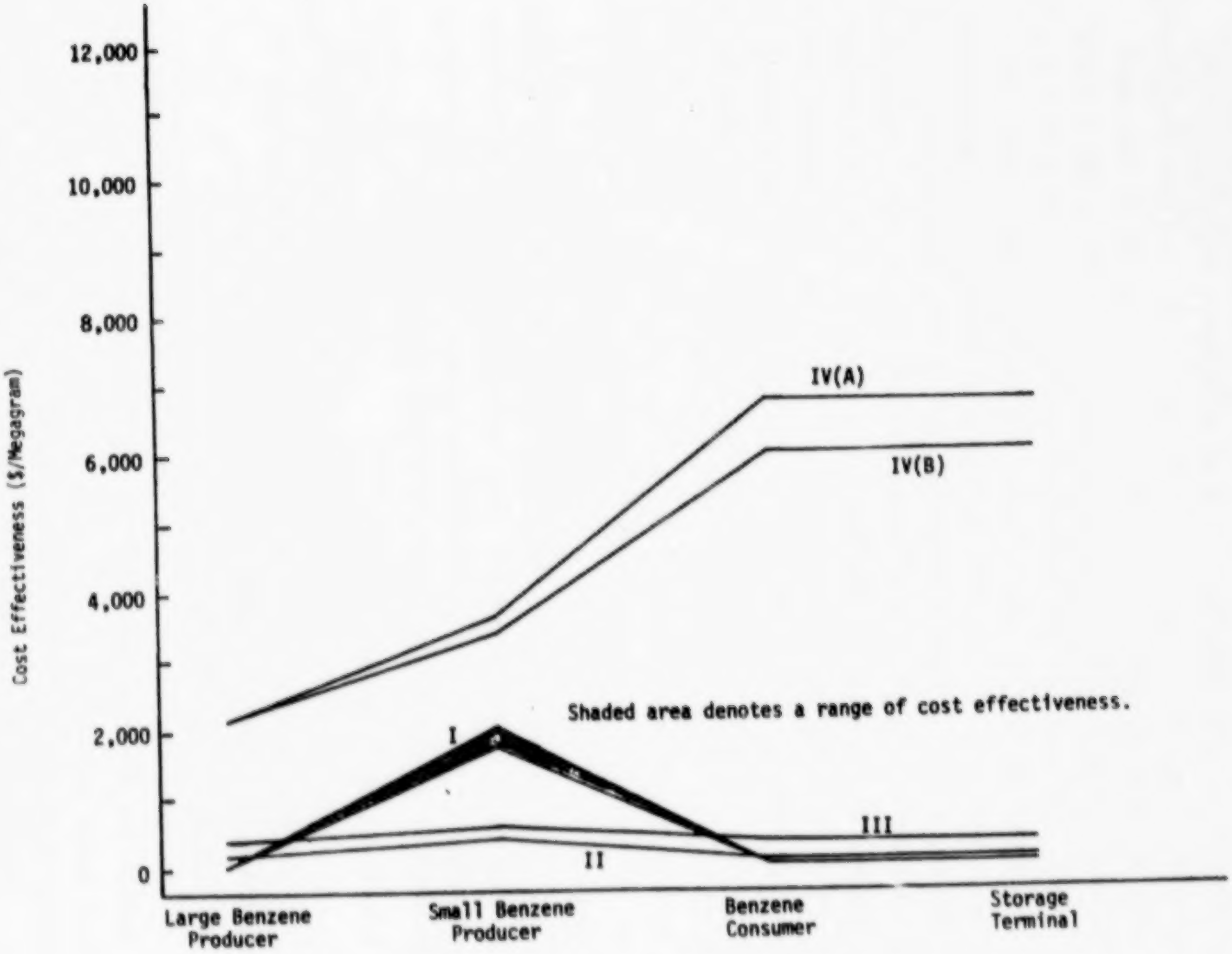

Figure 7-4. Cost effectiveness of control options for new facilities.

Table 7-33. TOTAL ESTIMATED NATIONAL EMISSIONS, CAPITAL COSTS, AND ANNUALIZED COSTS OF CONTROL OPTIONS

Emissions source and control option	National emissions (Mg/yr)	Total capital cost ($)	Total annualized cost ($)	Cost effect. ($/Mg)
Existing benzene storage tanks				
0-Baseline[a] (1979)	2,200	0	0	--
I	2,200	240,000	70,000	--
II	2,000	540,000	42,000	210
III	850	7,300,000	970,000	720
IV	510	11,000,000	1,600,000	950
V(A)	420	35,000,000	10,000,000	5,600
V(B)	320	29,000,000	9,300,000	4,900
New benzene storage tanks				
0-Baseline[a] (1985)	930	0	0	--
I	920	73,000	20,000	2,000
II	290	1,700,000	99,000	150
III	170	2,700,000	260,000	340
IV(A)	140	12,000,000	3,300,000	4,200
V(B)	110	9,500,000	3,100,000	3,800

[a] No additional standard.

The regulation having the most widespread impact would reduce fugitive benzene emission by 78 percent at plants having product streams of greater than 10 percent benzene by volume. This regulation would impact all new and existing benzene producers, consumers, and bulk storage terminals.

The second regulation would limit benzene from maleic anhydride plants. Benzene emissions from existing plants would have to be reduced to 0.30 kilograms of benzene per 100 kilograms of benzene fed into the reactor, and benzene emissions from new sources would have to be eliminated. Benzene emissions during a control system malfunction could not exceed those that would occur if the benzene feed were shut off to all reactors as soon as practicable after the malfunction began.

The third regulation would limit benzene emissions from process vents at existing and new ethylbenzene and styrene (EB/S) plants to 5 parts per million by volume (ppmv) on a dry basis, corrected to 3 percent oxygen. Excess emissions due to startup, shutdown, or malfunction would have to be combusted by a flare or flares, producing limited visible emissions, which generates no longer than 2 hours during startup, no longer than 2 hours during shutdown, and at all times during malfunction.

Table 7-34 presents the ranges of capital and annualized costs required for a model plant to comply with each of the three proposed regulations. The ranges of costs considered in the development of a regulation for controlling benzene emissions from benzene storage facilities are also presented for comparison.

7.4 ECONOMIC IMPACT ANALYSIS OF THE CONTROL OPTIONS

7.4.1 Introduction

This section discusses the potential economic impacts of the benzene storage control options on the model plants. First the economic characteristics of the plants are described in their baseline state. Then the effects of the various costs and credits associated with each control option are shown for each kind of model plant. The discounted cash flow method is used in the analysis, and a sample calculation is included to aid in the exposition.

7.4.2 Baseline Return on Investment (ROI) and Operating Ratios

Table 7-35 computes the current return on investment (ROI) in the petroleum and coal products industry using the discounted cash flow

Table 7-34. RANGE OF CAPITAL AND ANNUALIZED COSTS FOR CONTROLLING BENZENE EMISSIONS FROM AN INDIVIDUAL MODEL PLANT

Regulation	Capital cost (dollars)		Annualized cost[a] (dollars)	
	Existing plant	New plant	Existing plant	New plant
Benzene storage tanks	0-284,080	0-266,080	(1000)-71,800	0-68,500
Large producers	0-284,080	0-266,080	(1000)-71,800	0-68,500
Small producers	7000-250,270	6100-241,870	1900-71,300	1600-66,700
Consumer/bulk storage terminals	0-230,530	0-225,730	0-69,800	0-67,200
Benzene fugitive emissions	57,000-253,000	51,000-223,000	14,000-50,000	12,000-40,000
Maleic anhydride plants	1,160,000-1,400,000	---	442,000	---
Ethylbenzene/storage plants	0-555,000	---	(150,000)-26,000	---

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[a] Includes recovery credits, indicated in parenthesis.

Table 7-35. RETURN ON INVESTMENT FOR PETROLEUM AND COAL PRODUCTS INDUSTRY[32]

Number	Item			
1	Current assets		$40,625.50[a]	
2	Other assets		44,237.50[a]	
3	Net depreciable assets	59,701.00[a]		
4	Accumulated depreciation	58,296.00[a]		
5	Gross depreciable assets (no. 3 + no. 4)		117,997.00[a]	
6	Mineral rights, etc.		21,559.00[a]	
7	Total assets (sum of nos. 1,2,5,6)			224,419.00[a]
8	Net profit after tax		12,767.00[a]	
9	Depreciation		7,698.00[a]	
10	Cash flow (no. 8 + no. 9)			20,465.00[a]
	Capital recovery coefficient (no. 10 ÷ no. 7)			0.09119
	Depreciation rate (no. 9 ÷ no. 5)			0.0652
	Asset life (no. 5 ÷ no. 9)x1.25			19 years
	Return on investment[b]			6.2 percent
	Ratio of net income to revenue			.071

[a] Dollar figures are in millions of 1978 dollars, stocks are averages for the year, flows are totals for the year.

[b] The return on investment is the value for r which satisfies the following formula:

$$\text{Capital recovery coefficient} = \frac{r}{1-(1+r)^{-\text{Life of asset}}}$$

The formula was solved for the value 0.062 percent = r given the asset life of 19 years and the capital recovery coefficient of 0.09119.

method of analysis. The baseline parameters in Table 7-35 are assumed to be representative of the current economic conditions facing benzene producers. Table 7-36 shows a similar computation for the industrial chemicals and synthetics industry, which is assumed to be representative of benzene consumers. The procedure computes the net cash inflow to the industry as a result of its operations, and divides this figure by an appropriate measure of the stock of assets tied up in the industry. The quotient of cash flow over assets is called the capital recovery coefficient. Given the capital recovery coefficient and the average lifetime of the assets making up the capital stock, the return on investment can be computed by the discounted cash flow method.

The following paragraphs of this section describe in some detail the general procedure outlined above, and step through the application of the procedure to the petroleum and coal products industry.

The cash flow into the petroleum and coal products industry is computed from published income statement data by adding depreciation to after tax profit. This measure of money inflow is more appropriate than using net accounted profit because the depreciation flow is not actually a cash outflow, but merely an accounting convention. Referring to Table 7-35, the cash flow is $20,465 million ($12,767 million + $7,698 million).

The amount of resources tied up in the industry must be evaluated at original cost, not after subtracting the accumulated depreciation. This is done to facilitate the comparison of the initial investment to a typical year of cash inflow--the depreciated value of assets has no meaning in discounted cash flow analysis. Referring to Table 7-35, the total assets figure is $224,419 million.

Now the average lifetime of the assets, based on the depreciation reported, is computed. The depreciation rate is the annual percentage of decay of assets. The best available way to estimate this rate is to divide the annual flow of accumulated depreciation by the gross depreciable assets. In the petroleum and coal products industry, the result is $7,698 million divided by $117,997 million, or about 6.52 percent. If 6.52 percent of an asset decays every year, then, assuming straight line

Table 7-36. RETURN ON INVESTMENT FOR INDUSTRIAL CHEMICALS AND SYNTHETICS[33]

Number	Item			
1	Current assets		$20,567.00[a]	
2	Other assets		8,830.25[a]	
3	Net depreciable assets	24,934.00[a]		
4	Accumulated depreciation	25,210.25[a]		
5	Gross depreciable assets (no. 3 + no. 4)		50,144.25[a]	
6	Mineral rights, etc.		1,124.75[a]	
7	Total assets (sum of nos. 1,2,5,6)			80,666.25[a]
8	Net profit after tax		4,036.00[a]	
9	Depreciation		3,253.00[a]	
10	Cash flow (no. 8 + no. 9)			7,289.00[a]
	Capital recovery coefficient (no. 10 ÷ no. 7)			0.09036
	Depreciation rate (no. 9÷ no. 5)			0.0648
	Asset life (no. 5 ÷ no. 9)x1.25			19 years
	Return on investment[b]			6.2 percent
	Ratio of net income to revenue			0.068

[a] Dollar figures are in millions of 1978 dollars, stocks are averages for the year, flows are totals for the year.

[b] The return on investment is the value for r which satisfies the following formula:

$$\text{Capital recovery coefficient} = \frac{r}{1-(1+r)^{-\text{Life of asset}}}$$

The formula was solved for the value 0.062 percent = r given the asset life of 19 years and the capital recovery coefficient of 0.09036.

depreciation, the asset will be fully decayed after 1 divided by 0.0652 years, or 15.33 years. Thus, the average asset life is estimated to be 15.33 years. However, the problem with this estimate is that accounting depreciation will usually overestimate the true depreciation rate of an asset because Federal tax laws allow corporations to use accelerated depreciation to lower their taxes. The usual rule of thumb in adjusting asset life to account for accelerated depreciation is to inflate the asset life implied by the accounting depreciation rate by 25 percent. Thus, the asset life is estimated to be 19 years (15.34 x 1.25).

The capital recovery coefficient is the quotient of the cash flow divided by the capital asset stock. (When the coefficient is calculated using assumptions about asset lifetime and rate of return on investment instead of cash flow and capital asset stock, it is called a capital recovery factor.) The return on investment is the rate of interest one would have to charge to equate the discounted values of the incoming flows of cash to the original investment. In the present case, the initial investment of $224,419 million earns money at the rate of $20,465 million per year for a period of 19 years. Thus, given an asset life of 19 years, it is necessary to find the value of r that satisfies the following equation:

$$224{,}419 = \frac{20{,}465}{(1+r)} + \frac{20{,}465}{(1+r)^2} + \frac{20{,}465}{(1+r)^3} + \cdots + \frac{20{,}465}{(1+r)^{19}}$$

It can be shown that this formula is exactly equivalent to:

$$\frac{20{,}465}{224{,}419} = \frac{r}{1-(1+r)^{-19}}$$

which can be solved to get r = 0.062, representing a 6.2 percent return on investment.

Table 7-36 shows the results of a similar analysis on the industrial chemicals and synthetics industry, with the resulting value of the return on investment substantially the same as the 6.2 percent ratio calculated for the petroleum and coal products industry. The asset life and depreciation rates are almost identical, as are the ratios of net profit to revenue. In the following analysis, ROI is rounded to 10 percent and the asset life to 20 years for both producers and consumers. This simplifying adjustment assures that estimates of the potential negative economic impacts of the control options will be conservative (i.e., slightly exaggerated.

7.4.3 Example Calculation of Economic Impacts

The throughput and cost characteristics of the model plants developed in earlier sections of this report are summarized for ease of reference in Table 7-37. These numbers form the basis for the computation of two fundamental measures of impact on the model plants. The first measure is the change in the rate of return on the overall plant and equipment as a result of the expenditures stemming from compliance with an option, under the assumption that price and quantity sold remain unchanged. This measurement is intended to be instructive of the potential loss in earnings the plant would suffer if it were totally unable to pass on any of the increased costs. The opposite polar case, that of complete cost passthrough, forms the basis of the second measure of impact to be computed here. The second measure is the new price that the model plants would have to charge in order to maintain a 10 percent return on investment, assuming no change in quantity sold. In order to illustrate the method used in computing these impact measures, this section shows two sample calculations, one for a large benzene producer faced with Control Option III, and one for a benzene consumer faced with Control Option III. Throughout this section, the final results of the computations are rounded in order to improve readability and not create an exaggerated sense of precision in the results. Exceptions to this rule occur when greater precision is required to show small differences between two numbers. Intermediate calculations are carried out before rounding.

7.4.3.1 Baseline Characteristics of Large Benzene Producer in Example Calculation. In order to evaluate the option-induced changes in asset stocks and cash flows for the model plant, it is first necessary to compute baseline stocks and flows. Given the throughput of the plant from Table 7-37 and a price of benzene of \$0.34 per liter, revenues are computed for the model plant as \$76.36 million (\$0.34/liter x 224.6 million liters). It is likely that the benzene operations of the large producer are only a small part of a large petrochemical operation so that these

Table 7-37. THROUGHPUT COST SUMMARY FOR MODEL PLANTS

Plant	Control option	Benzene throughput (10^6 liters per year)	Capital cost for capital with 15-year life ($)	Capital cost for capital with 10-year life ($)	Total annualized cost ($)
Existing facilities					
Large producer	I	224.6	0	0	0
	II	224.6	0	10,400	(1,000)[a]
	III	224.6	25,400	141,800	21,000
	IV	224.6	25,400	191,500	29,100
	V(A)	224.6	284,100	0	68,000
	V(B)	224.6	242,000	0	71,800
Small producer	I	46.3	0	7,000	2,200
	II	46.3	0	7,000	2,200
	III	46.3	0	36,800	5,700
	IV	46.3	0	65,500	10,700
	V(A)	46.3	250,300	0	71,300
	V(B)	46.3	208,200	0	65,700
Consumer and bulk storage terminal	I	42.1	0	0	0
	II	42.1	0	0	0
	III	42.1	0	17,100	2,300
	IV	42.1	0	33,400	5,000
	V(A)	42.1	230,500	0	69,800
	V(B)	42.1	188,500	0	62,100
New facilities					
Large producer	I	224.6	0	0	0
	II	224.6	25,400	56,100	5,200
	III	224.6	25,400	96,000	11,200
	IV(A)	224.6	266,100	0	66,400
	IV(B)	224.6	244,000	0	68,500
Small producer	I	46.3	0	6,100	1,900
	II	46.3	0	44,600	4,000
	III	46.3	0	68,900	8,100
	IV(A)	46.3	241,900	0	66,700
	IV(B)	46.3	199,800	0	64,200
Consumer and bulk storage terminal	I	42.1	0	0	0
	II	42.1	0	15,100	100
	III	42.1	0	28,200	2,200
	IV(A)	42.1	225,700	0	67,200
	IV(B)	42.1	183,700	0	61,200

[a] Credit is indicated by parenthesis.

benzene revenues are only a small part of the total revenue of the entire operation. The question arises as to the separability of the benzene facilities from the rest of the operation, and the effect that the assumption of separability has on the computed impacts. It can be argued that the multiproduct firm has at least as much flexibility as a single-product firm, so that by separating the benzene facilities from the rest of the operation as if it were a separate plant, an upper bound is set on the impacts--the multiproduct firm would be able to find more ways to minimize impacts than the conceptual plant producing benzene only.

Given the revenue above and the ratio of net income to revenue of 0.071 as reported in Table 7-35, the net after-tax profit or income of the model plant from benzene operations is estimated to be \$5.42 million (0.071 x \$76.36 million). Given revenue and net profit, the assets of the firm are computed as follows. Recall that cash flow divided by assets gives the capital recovery coefficient; i.e.,

$$F = \frac{CF}{A} \qquad (7\text{-}1)$$

where F = capital recovery coefficient, CF = cash flow, and A = assets. Further, cash flow equals net income plus depreciation, as shown in the following formula:

$$CF = NI + DEPR \qquad (7\text{-}2)$$

where NI = net income, and DEPR = depreciation. Using an asset life of 20 years and applying the rule of thumb relating asset life to depreciation life, a depreciation life of 16 years results, implying a depreciation rate of 0.0625. Substituting this relation into Equations 7-1 and 7-2 produces the following relationship:

$$F = \frac{NI + (0.0625 \times A)}{A}$$

Solving for A gives:

$$A = \frac{NI}{(F - 0.0625)}$$

From the equations for calculating the return on investment, the capital recovery coefficient for a 10 percent return on investment with a lifetime of 20 years is 0.11746. Using the previously computed value of NI of

$5.42 million, A is computed to be $98.62 million. Now rearranging Equation 7-1, CF = F x A. The cash flow of the model plant is thus:

$$CF = 0.11746 \times \$98.62 \text{ million} = \$11.58 \text{ million}$$

Similarly, solving for DEPR as the product of the depreciation rate and the stock of assets:

$$DEPR = 0.0625 \times \$98.62 \text{ million} = \$6.16 \text{ million}$$

The total revenue of a firm less the cost of goods sold gives the before tax profit. At the corporate tax rate of 46 percent,[a] the following relation is applicable:

$$NI = (\text{Revenue} - \text{Cost of goods sold}) \times (1-0.46)$$

Solving for the cost of goods sold:

$$\text{Cost of goods sold} = \text{Revenue} - (NI/0.54)$$

$$= \$76.36 \text{ million} - \frac{\$5.42 \text{ million}}{0.54} = 66.32 \text{ million}$$

It will be convenient later on in the calculations to break the cost of goods sold into two components, a depreciation component and a "miscellaneous" component, which includes all expenses of the firm except depreciation and income tax. Defining the "miscellaneous" component as S yields:

$$\text{Cost of goods sold} = S + DEPR.$$

Then, solving for S:

$$S = \text{Cost of goods sold} - DEPR$$

$$= \$66.32 \text{ million} - \$6.16 \text{ million} = 60.16 \text{ million}.$$

Because the baseline estimates for cash flow, net income, depreciation, miscellaneous annual costs, revenue, and assets for the large producer in our example calculation are now available, the impacts can be computed.

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[a] Note that the marginal tax rate, MTR, is identical to the corporate tax rate for corporations with very high taxable incomes.

7.4.3.2 Impacts for Large Benzene Producer in Example Calculation. Reference to Table 7-37 shows that the costs for the large producer under Option III are broken down as $25,400 expended on a capital investment for capital with a 15-year life, $141,800 on capital with a 10-year life, and $21,000 total annualized cost. The total annualized cost includes capital recovery allowances, capital overhead charges, and annual costs for all other aspects of compliance with the option--maintenance, inspection, recovery credits, and labor. It is convenient to break down the total annualized cost reported in Table 7-37 as follows:

$ 3,340	Capital recovery for capital with a 15-year life
23,077	Capital recovery for capital with a 10-year life
-5,417	All other annual costs and credits
$ 21,000	Total annualized cost

The capital recovery charges are obtained by multiplying the capital investment (e.g., C15 for capital with a 15-year life) by the capital recovery factors for a 10 percent return on investment and the appropriate asset life. For 10-year assets the factor is 0.1627, and for 15-year assets the factor is 0.1315. The "all other" component includes the capital overhead costs, and is calculated as the residual between the total annualized cost and the combined capital costs. Because one component of the "other" annual costs is a credit for benzene not lost to emissions, the "all other" component costs may be either positive or negative.

Having separated out the costs in this way, the change in return on investment that can be attributed to the option can now be computed. The new cash flow after the imposition of the option is:

$$CF^* = (PQ - S - M - DEPR^*)(1 - 0.46) + DEPR^*$$

where

PQ = price x quantity sold, which yields revenue

M, the miscellaneous annual costs and credits of the option

= total annualized costs (TAC) - (C15 x 0.1315 + C10 x 0.1627)

DEPR* = DEPR + (C15 + C10) x 0.0625

C15 = the capital outlay for the assets with a 15-year life required by the option

C10 = the capital outlay for the assets with a 10-year life required by the option.

Because by assumption, price and quantity remain unchanged, revenue also remains unchanged, and the only differences in cash flow attributed to the option are the increased annual costs of the option, M, which become a direct charge against before-tax revenue, and the change in depreciation charges from DEPR to DEPR*. Using the equations for DEPR* and CF*, DEPR* is $6.17 million, and CF* is $11.59 million. (The baseline cash flow was $11.58 million.)

Recall that in the baseline case, the rate of return was the value of r that satisfies the following equation:

$$\frac{CF}{Assets} = \frac{r}{1-(1+r)^{-20}}$$

Multiplying both sides by Assets:

$$CF = \frac{r}{1-(1+r)^{-20}} \times Assets$$

By identical reasoning it can be shown that the rate of return upon implementation of an option is the value of r that satisfies the following equation:

$$CF^* = \left(\frac{r}{1-(1+r)^{-20}}\right) \times Assets + \left(\frac{r}{1-(1+r)^{-10}}\right) \times C10 + \left(\frac{r}{1-(1+r)^{-15}}\right) \times C15$$

This equation can be solved for r because the values for CF*, Assets, C10, and C15 are available. Unfortunately, the form of the equation precludes solving it explicitly for r. Two practical alternatives in this case are (1) to let a computer solve the equation using numerical iteration, or (2) to use a Taylor series approximation. The latter method was chosen because within the narrow range of values for the impacts of this option, the Taylor series has neglegible approximation error.

Solving for r, the rate of return upon implementation of Option III is estimated to be 0.099767. The second impact, the price change that is just large enough to allow the firm to maintain its ROI, is now evaluated. The new cash flow necessary to maintain ROI is computed using the equation:

$$CF' = (A \times F) + (C10 \times F10) + (C15 \times F15) \qquad (7\text{-}3)$$

where

CF' = the new cash flow needed to maintain ROI,

F10 = the capital recovery factor for 10 percent ROI and a 10-year asset life,

F15 = the capital recovery factor for a 10 percent ROI and a 15-year asset life.

All other symbols have already been defined. Because CF' is related to the new price as described in the following equations:

$$CF' = NI' + DEPR^* \qquad (7\text{-}4)$$

$$NI' = 0.54(P'Q-S-M-DEPR^*) \qquad (7\text{-}5)$$

where NI' = new net income and P' = new price, Equations 7-3, 7-4, and 7-5 can be solved explicitly for P' as follows:

$$P' = \frac{1}{Q}\left[\frac{(A \times F)+(C10 \times F10)+(C15 \times F15)-(DEPR^* \times 0.46)}{0.54} + S + M\right] \qquad (7\text{-}6)$$

Substituting the numbers already obtained for the variables on the right side of Equation 7-6, P' = $0.340154 per liter for the example calculation. This represents a price increase of about five hundredths of 1 percent.

This completes the example calculation for the large benzene producer under Option III. The methodologies have been shown for computing the ROI assuming no change in price, and the price assuming no change in ROI, where all the information used as input to the calculation is found in Tables 7-35 and 7-37. Similar methodologies are shown for estimating the impacts on the consumers of benzene.

7.4.3.3 Baseline Characteristic of Benzene Consumers in Example Calculation. The analysis of the benzene consumer differs from that for a benzene producer in two fundamental ways. First, the costs of an option are not reflected in a change in price or ROI for benzene, but instead in a change in price or ROI on a product containing benzene. Second, the benzene consumer must pay more for benzene if the producers can pass on their cost increases instead of absorbing them. That is, the consumer has two potential sources of additional costs if the option is implemented: (1) The firm's own capital and annual costs for bringing the plant into compliance, and (2) the increased price the firm might have to pay for benzene as a result of costs imposed on producers.

Table 7-38 shows the prices and throughputs for three different types of benzene consumers. These three types of consumers utilize about 85 percent of all benzene consumed. The outputs of the plants are based on the benzene input of the model plant and the fixed relation between benzene input and final product output based on the chemical reactions involved in manufacture. For example, in a stoichiometric reaction involving the manufacture of styrene, 78.1 kilograms of benzene would combine with 28.1 kilograms of ethylene to eventually produce 104.1 kilograms of styrene and 2.1 kilograms of hydrogen gas. However, the typical yield attained in practice is about 84 percent of the theoretical yield. Thus, 78.1 kilograms of benzene gives about 87.44 kilograms of styrene. Based on the fact that benzene weighs 0.883 kg per liter, the output of the model styrene plant is computed to be:

$$42.1 \text{ million liters benzene} \times \frac{0.883 \text{ kg benzene}}{\text{liter benzene}} \times \frac{87.44 \text{ kg styrene}}{78.1 \text{ kg benzene}}$$

$$= 41.61 \text{ million kg of styrene}$$

Given the price and quantity (throughput) data from Table 7-38 and the baseline operating ratios from Table 7-36, the same methodology that was used to compute the baseline operating characteristics of the model producer plant is used to compute the operating characteristics of the model consumer plant. The step-by-step calculations are shown here for the styrene plant:

Revenue = Price x Quantity = PQ = \$27.50 million

NI = 0.068 x Revenue = \$1.87 million

A, Assets = NI/(F-0.0625) = \$34.02 million

CF = F x A = \$4.00 million

Table 7-38. CHARACTERISTICS OF MODEL CONSUMER PLANTS[34, 35]

Type of plant	Price	Quantity
Cumene	$0.43/kg.	54.218 million kg.
Styrene	$0.661/kg.	41.61 million kg.
Cyclohexane	$0.396/liter	51.033 million liters

$$\mathrm{DEPR} = 0.0625 \times \mathrm{Assets} = \$2.13 \text{ million}$$

$$\text{Cost of Goods Sold} = \text{Revenue} - (\mathrm{NI}/0.54) = \$24.04 \text{ million}$$

$$S = \text{Cost of Goods Sold} - \mathrm{DEPR} = \$21.91 \text{ million}$$

7.4.3.4 Impacts for Benzene Consumer Example Calculation. Impacts for the model consumer are computed in the same manner as for the producer except that two impacts are calculated. The first impact is computed based on the assumption that the benzene producers are unable to pass on their increased costs as higher prices. The second impact is computed based on the assumption that benzene producers are able to pass on all of their increased costs as higher prices. The only difference in the two calculations is that in the second calculation, the increase in the cost of benzene to the consumer is added into the miscellaneous component of total annualized cost. Here are the step-by-step computations in the no-change-in-benzene-price scenario:

$$\mathrm{DEPR}^* = \mathrm{DEPR} + (\mathrm{C10} + \mathrm{C15}) \times 0.0625 = \$2.13 \text{ million}$$

$$M = \mathrm{TAC}-(\mathrm{C15} \times 0.1315 + \mathrm{C10} \times 0.1627) = -\$482$$

$$\mathrm{CF}^* = (\text{Revenue}-S-M-\mathrm{DEPR}^*)(1-\mathrm{MTR}) + \mathrm{DEPR}^* = \$3.998 \text{ million}$$

$$r = 0.099926$$

$$\mathrm{CF}' = (\mathrm{Assets} \times 0.1175) + (0.1627 \times \mathrm{C10}) + (0.1315 \times \mathrm{C15})$$

$$= \$4.00 \text{ million}$$

$$P' = \frac{1}{Q}\left(\frac{\mathrm{CF}' - (\mathrm{DEPR}^* \times 0.46)}{0.54} + S + M\right) = 0.661090$$

In the second calculation, for the full-producer-cost-passthrough scenario, the formula for M changes to:

$$M = \mathrm{TAC}-(\mathrm{C15} \times 0.1315 + \mathrm{C10} \times 0.1627) + (P_b - \$0.34) \times 42.1 \text{ million liters}$$

where P_b = the highest price that the benzene producers might charge for benzene in order to maintain their ROI under the same control option for which the consumer impacts are computed. For reasons that are discussed in Sections 7.4.4.1 and 7.4.4.4, this price is always the price charged by the small existing benzene producer. In the example calculation, P_b = \$0.340191 per liter. Thus, because the model consumer uses

42.1 million liters of benzene per year, the cost increase for benzene is \$0.000191 per liter times 42.1 million liters, which equals \$8,041. In the no-change-in-benzene-price computation, M was a \$482 credit. In the full-producer-cost-passthrough scenario, M equals \$7,559.

Because everything else is the same under both options, only the calculations that depend on M must be changed. Running through the step-by-step calculations, CF* = \$3,994 million instead of \$3,998 million as was just calculated for the no-change-in-benzene price scenario. This reduction in cash flow implies a reduction in ROI. Solution of the Taylor series gives $r = 0.099767$, as opposed to the previous value of 0.099926. Substituting the larger value of M into the P' evaluation gives a new price of \$0.661283 instead of the \$0.661090 value computed earlier.

This concludes the example calculations for the benzene producer and consumer. For the producers, the methodologies have been shown for computing ROI assuming no change in price, and the change in price assuming no change in ROI. In reality, the producers will be likely to pass on some of the cost increase, and will have to absorb the rest. The estimation of the exact mix of passthrough and absorption is unnecessary because both impacts are inconsequential, so that any mix between the two would also be inconsequential.

For the consumer, four cases of impacts have been computed, including ROI and price changes based on no cost passthrough by producers, and ROI and price changes based on full cost passthrough by producers. In each case, the methodology is identical to that applied to producers. The ROI change is based on the assumption of no change in the price of the product produced, be it cumene, styrene, or cyclohexane, and the price change is computed based on the maintenance of a 10 percent ROI. The impacts calculated using the methodology discussed in the above examples are now presented.

7.4.4 Economic Impacts for Model Plants

Table 7-39 shows the impacts for the existing and new producer model plants, under the five control options for existing plants, and the four control options for new plants. Tables 7-40 and 7-41 show the impacts

Table 7-39. ECONOMIC IMPACTS FOR MODEL BENZENE PRODUCER PLANTS

Plant	Control option	ROI under assumption of no change in price	Percent change in ROI	Price under assumption of no change in ROI[a]	Percent change in price
Existing facility					
Large producer	I	0.100000	0.000	0.340000	0.000
	II	0.100001	0.001	0.340000	0.000
	III	0.099764	-0.236	0.340154	0.045
	IV	0.099680	-0.320	0.340209	0.062
	V(A)	0.099423	-0.577	0.340377	0.111
	V(B)	0.099414	-0.586	0.340383	0.113
Small producer	I	0.099907	-0.093	0.340061	0.018
	II	0.099907	-0.093	0.340061	0.018
	III	0.099707	-0.293	0.340191	0.056
	IV	0.099461	-0.539	0.340353	0.104
	V(A)	0.097178	-2.822	0.341862	0.548
	V(B)	0.097438	-2.562	0.341687	0.496
New facility					
Large producer	I	0.100000	0.000	0.340000	0.000
	II	0.099922	-0.078	0.340051	0.015
	III	0.099857	-0.143	0.340093	0.027
	IV(A)	0.099441	-0.559	0.340365	0.107
	IV(B)	0.099443	-0.557	0.340364	0.107
Small producer	I	0.099920	-0.080	0.340052	0.015
	II	0.099741	-0.259	0.340169	0.050
	III	0.099537	-0.463	0.340303	0.089
	IV(A)	0.097344	-2.656	0.341751	0.515
	IV(B)	0.097502	-2.498	0.341644	0.483

[a] Units for price: dollars per liter of benzene.

TABLE 7-40. ECONOMIC IMPACT FOR MODEL BENZENE CONSUMER PLANTS UNDER ASSUMPTION OF FULL COST ABSORPTION BY PRODUCERS

Plant	Control option	ROI under assumption of no change in price	Percent change in ROI	Price under assumption of no change in ROI[a]	Percent change in price
Existing facilities					
Cumene	I	0.100000	0.000	0.430000	0.000
	II	0.100000	0.000	0.430000	0.000
	III	0.099912	-0.088	0.430069	0.016
	IV	0.099817	-0.183	0.430145	0.034
	V(A)	0.098068	-1.932	0.431537	0.357
	V(B)	0.098302	-1.698	0.431350	0.314
Styrene	I	0.100000	0.000	0.661000	0.000
	II	0.100000	0.000	0.661000	0.000
	III	0.099926	-0.074	0.661090	0.014
	IV	0.099846	-0.154	0.661187	0.028
	V(A)	0.098374	-1.626	0.662986	0.300
	V(B)	0.098571	-1.429	0.662744	0.264
Cyclohexane	I	0.100000	0.000	0.396000	0.000
	II	0.100000	0.000	0.396000	0.000
	III	0.099899	-0.101	0.396074	0.019
	IV	0.099789	-0.211	0.396154	0.039
	V(A)	0.097774	-2.226	0.397633	0.412
	V(B)	0.098043	-1.957	0.397434	0.362
New facilities					
Cumene	I	0.100000	0.000	0.430000	0.000
	II	0.099968	-0.032	0.430026	0.006
	III	0.099892	-0.108	0.430085	0.020
	IV(A)	0.098135	-1.865	0.431484	0.345
	IV(B)	0.098329	-1.671	0.431328	0.309
Styrene	I	0.100000	0.000	0.661000	0.000
	II	0.099973	-0.027	0.661033	0.005
	III	0.099910	-0.090	0.661110	0.017
	IV(A)	0.098430	-1.570	0.662918	0.290
	IV(B)	0.098594	-1.406	0.662716	0.260
Cyclohexane	I	0.100000	-0.000	0.396000	0.000
	II	0.099963	-0.037	0.396027	0.007
	III	0.099876	-0.124	0.396090	0.023
	IV(A)	0.097851	-2.149	0.397577	0.398
	IV(B)	0.098074	-1.926	0.397711	0.356

[a] Units for price: dollars per kilogram for cumene and styrene, dollars per liter for cyclohexane.

Table 7-41. ECONOMIC IMPACT FOR MODEL BENZENE CONSUMER PLANTS UNDER ASSUMPTION OF FULL COST PASSTHROUGH BY PRODUCERS

Plant	Control option	ROI under assumption of no change in price	Percent change in ROI	Price under assumption of no change in ROI[a]	Percent change in price
Existing facilities					
Cumene	I	0.099940	-0.060	0.430047	0.011
	II	0.099940	-0.060	0.400047	0.011
	III	0.099723	-0.277	0.430219	0.051
	IV	0.099468	-0.532	0.430421	0.098
	V(A)	0.096239	-3.761	0.432993	0.696
	V(B)	0.096642	-3.358	0.432669	0.621
Styrene	I	0.099950	-0.050	0.661061	0.009
	II	0.099950	-0.050	0.661061	0.009
	III	0.099767	-0.233	0.661283	0.043
	IV	0.099553	-0.447	0.661543	0.082
	V(A)	0.096835	-3.165	0.664867	0.585
	V(B)	0.097174	-2.826	0.664448	0.522
Cyclohexane	I	0.099931	-0.069	0.396050	0.013
	II	0.099931	-0.069	0.396050	0.013
	III	0.099680	-0.320	0.396233	0.059
	IV	0.099386	-0.614	0.396447	0.113
	V(A)	0.095666	-4.334	0.399180	0.803
	V(B)	0.096129	-3.871	0.398835	0.716
New facilities					
Cumene	I	0.099940	-0.060	0.430047	0.011
	II	0.099778	-0.222	0.430175	0.041
	III	0.099544	-0.456	0.430361	0.084
	IV(A)	0.096305	-3.695	0.432940	0.684
	IV(B)	0.096669	-3.331	0.432647	0.616
Styrene	I	0.099950	-0.050	0.661061	0.009
	II	0.099814	-0.186	0.661227	0.034
	III	0.099616	-0.384	0.661466	0.071
	IV(A)	0.096891	-3.109	0.664799	0.575
	IV(B)	0.097197	-2.803	0.664420	0.517
Cyclohexane	I	0.099931	-0.069	0.396050	0.013
	II	0.099744	-0.256	0.396186	0.047
	III	0.099474	-0.526	0.396383	0.097
	IV(A)	0.095742	-4.258	0.399123	0.789
	IV(B)	0.096160	-3.840	0.398812	0.710

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[a] Units for price: dollars per kilogram for cumene and styrene, dollars per liter for cyclohexane.

for three consumer plants under the same options. The reader is cautioned that the data used in these calculations do not support the level of accuracy expressed in the tables. The numbers do indicate that the economic impacts generally are very small; that price changes, if any, are likely to be increases; and that changes in the return on investment, if any, are likely to be decreases. The numbers also show the relative magnitude of changes among model plants and control options. The following sections present detailed discussions of these impacts.

7.4.4.1 Economic Impacts for Large Existing Benzene Producer. The existing large producer has relatively little trouble meeting the requirements of any option. In Option I the tank configuration is such that the large producer suffers no impacts whatsoever. In the other options, the cost and asset bases are so large that the additions to the costs and assets occasioned by the control options are inconsequential by comparison. Even so, it is instructive to note that Options V(A) and V(B) have much larger impacts than the other options. The changes in return on investment or price are almost twice as large under Option V than under Option IV, the next less expensive option.

7.4.4.2 Economic Impacts for Small Existing Benzene Producer. As with the large existing producer, the impacts for the small existing producer can be regarded as inconsequential with the possible exception of the vapor control options, Options V(A) and V(B). Under these options the price change is roughly one-half of 1 percent. The impacts of these two options are much larger for the small producer than they are for the large producer because both large and small producers must install roughly the same amount of capital, but the large producer spreads the expenditure over a much larger throughput, thereby achieving an economy of scale relative to the small producer. The effect would be even more noticeable for real-world producers that are smaller than the small producer model plant.

7.4.4.3 Economic Impacts for Existing Benzene Consumers. The impacts for the consumers are similar in pattern to those of the small producer--that is, the impacts for the tank reconfiguration options, Options I through IV, are quite small, but in comparison, the impacts for vapor control options are quite large.

The reason that the impacts for the consumers differ for the different chemicals being produced is because the consumers vary as to the percent of benzene embodied in their final output, and as to the total asset base. The asset bases of the three model consumers are $28.85 million for cumene, $34.02 million for styrene, and $25.00 million for cyclohexane. Because all three plants have the same costs imposed, it is expected that the ROI will be most greatly affected in the cyclohexane model plant because it has the smallest asset base. Conversely, the smallest ROI change under a given option should occur in the styrene plant. The same reasoning holds for the price changes. Inspection of Table 7-40 shows this reasoning to be borne out by the figures.

The percentage of benzene embodied in the final output also affects the impacts computed for the producer cost passthrough scenario in Table 7-41. This is explained by considering the following figures. For the cumene producer, the revenue is $23.31 million, and the amount paid for benzene as an input is $14.322 million (0.340191/liter x 42.1 million liters). Thus, the value of benzene input is 61 percent of revenue. For styrene, the figure is 52 percent, and for cyclohexane it is 71 percent. Thus, a given increase in the price of benzene will have its greatest impact on cyclohexane producers, and its smallest impact on styrene producers. This pattern of passthrough cost impact is exactly the same as the pattern of impacts of their own costs, and because the effects are additive, the same overall pattern of relative impacts is expected under the cost passthrough scenario as existed under the no-change-in-benzene price scenario, except that the impacts would be larger. Inspection of Table 7-41 shows that this is true. Among all consumers, the largest changes in price and ROI occur for the cyclohexane producer. Therefore, this case is discussed in some detail. Note that the costs of Options V(A) and V(B) are seven to nine times larger than the cost for Option IV, the next less expensive option, but that no price increase exceeds 1 percent even under the assumption of full cost passthrough on the part of the producers. In judging the overall consequences of implementing the option, it must be remembered that consideration of the price increases in both benzene and products containing benzene is, in a sense, double counting. If one expects full cost passthrough by the producers, then the full impact on the economy is eventually felt through the price increases in products containing embodied benzene. The society loses buying power due to a price rise in intermediate goods such as benzene only when the price rise filters down to final goods and services. In this sense, the passthrough impacts are probably the most meaningful figures pertaining to benzene consumers. On the other hand, if the impacts of the option on an individual industry are of interest, then the passed-on increases from supplying industries are not directly applicable. Thus, the no-change-in-benzene-price impacts are most appropriate in assessing the consequences of the option on the benzene-consuming industries. In either interpretation, the price and ROI impacts listed in Tables 7-40 and 7-41 are inconsequential, with the possible exception of the vapor control options.

7.4.4.4 Economic Impacts for New Facilities. The economic impacts for new facilities differ from those for existing facilities primarily because the Petroleum Liquid Storage Tank NSPS requires that all new external floating-roof tanks have primary and secondary seals, and only the incremental costs of the options over the NSPS levels can logically be attributed to the control options analyzed here. That is, for existing facilities, the costs of going from the fixed-roof tank CTG to the control option is attributable to the control option, whereas for a new facility, only the costs of going from the NSPS to the control option is attributable to the control option. Another difference between the costs for new and existing facilities is that it is never more costly, and it is usually much cheaper, to upgrade to a particular specification when the equipment involved is still in design, rather than to retrofit existing equipment.

For the tank configuration options, Options I through III, the difference attributable to the NSPS baseline can make a considerable relative difference between comparable options applied to new and existing facilities. However, in absolute terms, because the existing plant impacts were already judged inconsequential, the new plant impacts (which are smaller) are perforce also inconsequential. In the case of the vapor control options, Options IV(A) and IV)B), the difference between new and existing plants is attributable to the savings of new over retrofit costs for the piping and switches. These differences are rather small, averaging 4.2 percent for Option IV(A) and 2.8 percent for Option IV(B). Thus, the new plant impacts repeat the pattern already observed for the existing plant impacts--the tank reconfiguration options are uniformly inconsequential, none amounting to more than a one-tenth of 1 percent rise in price, whereas the vapor control options are many times more expensive.

7.4.4.5 Summary of Economic Impacts for Model Plants. Two general observations serve to summarize the results of the economic analysis of the model plants:

(1) Except for the vapor control options, the impacts can be considered inconsequential. Among the tank configuration options, the largest price impact is a rise of 0.104 percent--a price change that would hardly be noticed in an industry subjected to the large increases in price imposed by foreign oil suppliers;

(2) The impacts attributed to the vapor control options are also quite small in comparison to the impacts imposed by foreign oil prices, but in comparison to the tank configuration options, the vapor control options are much more expensive. It is worthwhile to note that the vapor control options could possibly be the cheapest options for a very large producer. This would likely be the case for a plant that has or expects to have other vapor control requirements in addition to benzene tanks, or for a plant that already has much of the vapor control equipment in place. However, the general conclusion is that, for the model plants specified here, the vapor control options are decidedly less economical than the tank configuration options, costing roughly three to ten times as much. In individual cases, though, it might be economical for a specific plant to utilize a vapor control system.

7.4.5 Economic Impacts for Bulk Storage Terminals

The economic analysis for bulk storage terminals differs from that for producers and consumers in one main respect. The terminals are providing a service, whereas the producers and consumers are providing a product. The reason this is important is that the costs of storage services are only a small part of the overall cost of most products, but they constitute the whole output of terminal facilities. Earlier sections of this chapter have shown that the increases in costs resulting from the proposed control options affect the producers and consumers very little. Thus, the storage component of the $0.34 baseline price of benzene must be quite small. However, a similar analysis for terminals would reveal a different story because the storage cost component of their output is 100 percent. Unfortunately, there are no data available for computing price and ROI changes for terminals in as quantitative a way as was done for the producers and consumers of benzene. Thus, none are computed. Instead, the impacts are approached in a nonquantitative way. Because the service being offered by terminals is an almost perfect substitute for the terminal customer providing the same service, the following two propositions are true:

(1) Any price increase in terminal storage services cannot possibly raise the price of benzene or products derived from benzene very far above the prices computed for those products earlier in this chapter.

(2) As long as terminals pass on only the price increase necessary to cover their increased costs, terminal customers will not shift to other terminals or to self-provided services, because the costs of these options will have risen by the same amount.

Put another way, these two propositions can be viewed as essentially treating the terminal as an extension of the producer's or consumer's own plant. The only difference is that, instead of bearing the impacts directly, they are borne indirectly through the terminal owner.

When a benzene producer or consumer opts to use storage at a public terminal instead of storage at a self-owned facility, it must be because he or she views the terminal service as less costly than a self-owned facility. Even when the terminal is remote from the main plant site, so that the apparent reason for using the terminal is its location, the benzene producer or consumer always has the option of building a storage facility near the remote site serviced by the terminal. The decision to lease is evidence that the management of the benzene facility felt that leasing was cheaper than self-provision at the time the decision was made. The terminal must, therefore, be providing the storage services at a competitive price that just covers costs and a fair ROI. If the terminal were charging more than that price, the producers and consumers would self-provide. If the terminal were charging less, it would go out of business. The same argument holds after implementing an option, so that the impacts for a benzene producer or consumer who leases storage tanks would differ little from those of a producer or consumer who owns storage tanks. The lease price should go up by almost exactly the same amount as the total annualized cost of the option (ignoring differential tax treatments on the depreciation). If the terminal operator tried to pass on more than the associated costs, it would become advantageous for the benzene producer or consumer to self-provide. The terminal operator would not pass on less, because of his or her wish to maintain ROI. The terminal operator would sooner maintain ROI by using tanks to store other substances with physical properties similar to benzene such as lube oils, fuel oils, or glycols, rather than suffer a reduced ROI by providing benzene storage below cost. Because terminals have very few of their tanks in benzene service, this minor change in the mix of services provided could be performed with a minimum of disruption in overall terminal operations. Employment would be unlikely to change at all, and revenues would change only in response to cost changes.

Consumers and producers of benzene will not necessarily shift away from benzene storage at terminals as a result of increased prices for these services, because the costs of the substitute, self storage, will have gone up by roughly the same amount. Therefore, the cost considerations which caused them to lease rather than buy in the first place will not have changed as a result of implementing an option.

7.4.6 Analysis of Closure Option

The closure option is presumed to be the ultimate control for any hazardous substance. However, such a drastic measure as closure is rarely justified because of the excessive burden involved. The impacts of closure would be twofold. Direct impacts, such as a reduction in employment, and writing off of capital stock in the benzene-producing and benzene-consuming industries would affect the producers and consumers themselves. Indirect impacts, such as price increases, quality reductions, and reduced output would arise from the attempts of the downline users of benzene-derived substances to buy the benzene-derived substances from foreign sources or substitute other less suitable substances for them.

7.4.6.1 Direct Impacts on Benzene Producers and Consumers. A total ban on benzene would cause the people employed in benzene production to become unemployed or occupied by other jobs. The number of people so affected can be roughly estimated as follows. The 1976 Annual Survey of Manufactures[36] shows that for SIC 2911, Petroleum Refining, the value of shipments was \$77,507.3 million, with the industry employing 101,700 workers at that time. This implies a labor/output ratio of 1.31213×10^{-6} person-years per 1976-dollar of output. To restate the ratio in first-quarter 1979 dollars, it must be multiplied by the Bureau of Labor Statistics' producer price index for refined petroleum products in 1976[37], 276.6, and divided by the same index for first-quarter 1979[38], 350.6. The result is 1.0352×10^{-6} person-years per 1979 dollar of output. The total production of benzene in 1979 is estimated to be about 6,420 million liters or about \$2,183 million dollars, at the price of \$0.34 per liter.[39] Multiplying the person-years per dollar coefficient by the dollar value of total output gives the person-years embodied in the total output. The result is 2,260 person-years, a rough estimate of the number of jobs which would be displaced in the benzene-manufacturing sector in the event of closure. A similar computation for benzene consumers suggests that about 17,600 jobs would be displaced in the consuming industries, giving a total of 19,860 affected jobs. It is important to note, however, that the production of benzene is typically carried out in a facility that produces a variety of chemicals, not just benzene. It is likely that the individuals currently employed in benzene production would simply adjust the mixture of time they spend producing various outputs, adjusting out of benzene production and into other production; however, they would likely be employed at essentially the same job at the same place of work.

It is unlikely that any significant unemployment would result from closure.

A similar analysis holds for the other major factor of production, capital. The quantity of capital in benzene production can be computed in much the same way as capital was computed for the model plants. Recalling from Table 7-35 that the ratio of net income to revenue in the petroleum-refining industry is 0.071, the net income to the petroleum-refining industry that can be attributed to benzene operations is estimated as $155 million (0.071 x $2,183 million). From Table 7-35 the capital recovery coefficient for the petroleum-refining industry is 0.09119, and the depreciation rate is 0.0652. Substituting these values into the formula for assets derived from Equations 7-1 and 7-2, the capital stock of the petroleum-refining industry that is dedicated to benzene production is estimated at $6,156 million. A similar computation for the consumers of benzene gives $10,563 million (These estimates are very sensitive to small changes in the ratios used in the calculations and, therefore, should be considered only ballpark estimates.) Just as with labor, however, the capital involved in this production is likely to have alternative uses. Thus, if closure were imposed, it is unlikely that all or even a substantial part of the total capital affected would be totally written off. It would be placed into alternative service. To the extent that certain items of equipment were useful solely in benzene-related activities, these items would have to be scrapped, modified for non-benzene use, or sold to benzene producers located outside the U.S. This forced action would be the direct capital cost impact of the closure option.

7.4.6.2 Indirect Impacts on Users of Benzene-Derived Products. There are two substitution alternatives available to the users of benzene-derived products. The first is to purchase the same product from a foreign producer, and the second is to substitute a non-benzene product with similar characteristics. In the foreign-supply case, prices will be likely to rise reflecting the increased transportation costs of the foreign benzene, and the U.S. balance of payments will also suffer. Furthermore, the banning of U.S. benzene production, about 40 percent of world production, would create a worldwide upward shift in the supply curve for benzene, which could have the effect of increasing the world price of benzene while simultaneously reducing the total quantity produced.

In the case of substitution of non-benzene-derived inputs for benzene-derived products, the quality of the output produced from the substituted inputs will be likely to have fallen from the pre-closure level, and the price of the output may also rise. This is so in the absence of significant technical advances creating substitutes that are not now available. If a substitute input was available before the closure, the manufacturer would already have been using it unless it was less suitable, more costly, or both, when compared to the benzene-derived input being used at the time of the closure. Thus, if closure is implemented, the substitute is most likely to be less suitable, more costly, or both.

These indirect impacts, increases in prices, decreases in quality, or combinations of both, are the most important impacts that could be expected in the event of closure. Compared to the direct impacts, they would be much further reaching and potentially more expensive. A quantitative estimate of the cost of the indirect impacts is beyond the scope of this study.

7.5 SOCIOECONOMIC AND INFLATIONARY IMPACTS

7.5.1 Inflationary Impact Statement Thresholds

Executive Order 12044 requires that the inflationary impacts of major legislative proposals, regulations, and rules be evaluated. A regulation is considered a major action requiring the preparation of an inflationary impact statement if it exceeds either or both of the following thresholds:

(1) Annualized costs of compliance, including capital charges, equals $100 million per year

(2) Total additional cost of production exceeds 5 percent of the selling price of the product.

The following sections consider each of these thresholds in turn.

7.5.1.1 Annualized Cost Compared to $100 Million Threshold. In order to compute the total annualized cost of an option affecting plants in the United States in 1979, the number of such plants must be multiplied by the corresponding cost per plant. Utilizing the estimate that there were 28 large producers, 34 small producers, 77 consumers, and 4 bulk storage terminals existing in 1979, and using the cost data from Table 7-37, we find that the total annualized cost of implementing Control Option III in 1979 is \$968,100.

In calculating the annualized costs for 1980, the additional total annual costs for the new facilities constructed after 1979 must be added. Assuming that there is no reduction in the number of existing facilities, that there is a 5 percent annual growth rate in the number of facilities, and that the new facilities pay a full year's worth of the costs, the following expression can be used to compute the total annualized costs (TAC) in any year after 1979:

$$\text{TAC}_t = \text{TAC}_{1979} + [(1.05)^{t-1979} - 1][\#\text{ plants in 1979}][\text{cost/plant}]$$

Filling in the cost formula, assuming Option III for existing tanks and Option II for new tanks apply, the total annualized cost in 1985 is calculated to be \$1,066,626 (\$968,100 + \$98,526). Annualized costs for other combinations of options (i.e., other alternatives) and other years are displayed in Table 7-42. No cost for any combination in any year even approaches the \$100 million threshold; therefore, based on this criterion, none of the combinations represents a major impact.

In addition to the total annual cost of the combinations, the annual expenditures on new capital should be of some interest. These expenditures are calculated by multiplying the capital cost for each type of plant by the number of plants of that type and summing the results. In 1979, the total expenditures on new capital under Control Option III are calculated to be \$7,317,900. In subsequent years, the new capital expenditures become much smaller because only the plants that come into existence in that year need to buy the capital. In any year t, the number of plants that come into existence may be computed using the formula:

$$\text{New plants in year } t = [(1.05)^{t-1979} - (1.05)^{(t-1)-1979}][\#\text{ original plants}]$$

Thus, the formula for calculating the new capital expenditures, K, in year t, is:

$$K_t = (\text{new plants in year } t)(\text{capital cost/plant})$$

The total cost in 1985 for Control Option II applied to the new plants is thus:

Table 7-42. TOTAL ANNUALIZED COSTS ATTRIBUTABLE TO COMBINATIONS OF CONTROL OPTIONS FOR NEW AND EXISTING TANKS (FIRST-QUARTER 1979 DOLLARS)[a]

Year	Combinations of Control Options					
	I Old I New	II Old II New	III Old II New	IV Old III New	V(A) Old IV(A) New	V(B) Old IV(B) New
1979	$ 74,800	$ 46,800	$ 968,100	$1,583,600	$ 9,982,000	$ 9,274,300
1980	78,030	61,285	982,585	1,621,960	10,460,510	9,727,200
1981	81,421	76,494	997,794	1,662,238	10,962,946	10,202,745
1982	84,983	92,464	1,013,764	1,704,530	11,490,503	10,782,067
1983	88,722	109,232	1,030,532	1,748,936	12,044,438	11,226,355
1984	92,648	126,839	1,048,139	1,795,563	12,626,070	11,776,858
1985	96,770	145,326	1,066,626	1,844,521	13,236,783	12,354,886
1986	101,099	164,737	1,086,037	1,895,927	13,878,032	12,961,815
1987	105,644	185,119	1,106,419	1,949,904	14,551,344	13,599,091
1988	110,416	206,520	1,127,820	2,006,579	15,258,321	14,268,320
1989	115,427	228,991	1,150,291	2,006,088	16,000,647	14,970,827
1990	120,688	252,585	1,173,885	2,128,572	16,780,089	15,708,553

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[a] Each table entry is calculated by assuming that all new and existing facilities employ the combinations of control options specified in the column heading.

$$[1.05^6-1.05^5][(81{,}500\times28)+(44{,}600\times34)+(15{,}100\times77)+(15{,}100\times4)] = \$320{,}442$$

Capital costs for other combinations of control options and other years are shown in Table 7-43.

7.5.1.2 Production Costs Compared to Five Percent Threshold. The costs per liter calculated in the previous section translate to percentages of price of 0.46 percent for the consumer and 0.42 percent for the producer, when compared to the baseline price of $0.34 per liter[a]. These impacts are considerably smaller than the 5 percent threshold. Therefore, none of the options results in major impacts.

7.5.2 Foreign Trade Considerations

There are two aspects of foreign trade that must be considered in evaluating the feasibility of an option: (1) Will implementation of the option induce more importation of foreign goods, and (2) Will implementation of the option reduce U.S. exports of the goods? An affirmative answer to either question means that the option will worsen the U.S. balance of payments and lead to reduced domestic industrial production. Both questions could be answered in the affirmative if U.S. producers raised their prices to pass on new costs, while producers in other countries, who do not have to comply with U.S. laws, maintain their prices. In this case, both U.S. and foreign consumers would tend to substitute other countries' products for the U.S. output, reducing U.S. exports and increasing U.S. imports.

In the case of benzene, only about 3.5 percent of the product consumed in this country is imported, and only about 2.5 percent of the domestic production is exported. Even if these small quantities underwent fairly sizable proportional changes, their overall impact would not be large in relation to the whole market. However, given the smallness of the price changes expected to come about as a result of an option, it is unlikely that the quantities imported or exported would be greatly affected through price-induced substitution.

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[a] These cost-to-price ratios differ from the price change necessary to maintain ROI in that the government absorbs some of the total annualized costs through reduced taxes in the computation of price changes necessary to maintian ROI, whereas these cost-to-price ratios compare per-liter costs to baseline without considering where the costs are borne.

Table 7-43. ANNUAL EXPENDITURES ON NEW CAPITAL STOCK ATTRIBUTABLE TO COMBINATIONS OF CONTROL OPTIONS FOR NEW AND EXISTING TANKS (FIRST-QUARTER 1979 DOLLARS)

	Combinations of Control Options					
Year	I Old I New	II Old II New	III Old II New	IV Old III New	V(A) Old IV(A) New	V(B) Old IV(B) New
1979	$238,000	$529,200	$7,317,900	$11,005,600	$3,513,500	$2,912,300
1980	10,370	251,075	251,075	401,300	1,697,855	1,115,005
1981	10,888	263,629	263,629	421,365	1,782,748	1,170,755
1982	11,433	276,810	276,810	442,433	1,871,885	1,229,293
1983	12,005	290,651	290,651	464,555	1,965,480	1,290,758
1984	12,605	305,183	305,183	487,783	2,063,753	1,355,295
1985	13,235	320,442	320,442	512,172	2,166,941	1,423,060
1986	13,897	336,464	336,464	537,780	2,275,287	1,494,213
1987	14,592	353,288	353,288	564,669	2,389,053	1,568,924
1988	15,321	370,952	370,952	592,903	2,508,505	1,647,370
1989	16,087	389,500	389,500	622,548	2,633,930	1,729,738
1990	16,892	408,975	408,975	653,675	2,765,626	1,816,225

[a] Figures in table are expenditures for new capital in 1979 dollars and are calculated by assuming that all plants use the combinations of control options specified in the column headings.

7.5.3 Industry Output, Employment, and Growth Impacts

One concern with regulation is that the price change brought about by the implementation of an option might be sufficient to induce a change in quantity sold, which would, in turn, induce a change in employment in the industry. It is unlikely that the small price changes attributable to any of the control options would produce a noticeable change in either output or employment. Nonetheless, a simplified calculation of employment impacts is presented below to suggest approximate upper bounds on the changes in employment and output.

Because benzene is an intermediate good, its demand elasticity is the same as the elasticity of substitution for benzene in the manufacturing processes in which it is used. These elasticities can be estimated, but such an estimation is beyond the scope of this work. However, it has been shown that the price elasticity for inputs to production rarely exceeds unity. Thus, as a rough estimate of the upper bounds of the employment and output impacts of an option, changes in employment and output have been estimated under the assumptions that benzene consumers raise prices by 0.803 percent, the highest hike for any consumer in any option, and that the price elasticity is unity. Under the unitary elasticity assumption, a 0.803 percent rise in price implies a 0.803 percent fall in quantity sold, and under the assumption of fixed coefficients of production, this implies a 0.803 percent fall in employment. Thus, given the initial level of employment of 19,860 person-years computed in Section 7.4.6.1, a reduction in employment of 159 jobs is estimated as the maximum employment reduction in both industries under the most expensive option. It must be borne in mind, however, that this impact does not lead directly to the firing of 159 employees; it is quite likely that the displaced employees would simply become engaged in other production activities at the same places of work. Even if all 159 individuals became immediately unemployed, however, this event could hardly be characterized as a "major" impact on the economy.

The economic conditions in the petroleum and petrochemical industries have been a major concern because of the large and continuing rise in world oil prices which began in 1973. Certainly the enacting of controls which serve to further raise costs in these industries should receive double scrutiny because of this situation. For most industries, one of the prime concerns in regulation is the effect of the regulation on industry growth. The options evaluated here could possibly have some minor effects on industry growth; however, any effects they could have in this area would be quite inconsequential in comparison to the growth effects brought about by the increases in world oil prices and the actions of the government in the area of price regulations and supply allocations intended to combat these price increases. Furthermore, in the petroleum and petrochemical industries, unlike most industries in which growth is one of the primary goals, the primary goals seem now to be efficiency and conservation. Viewed in this light, those options in which benzene is recovered or prevented from escaping have a positive benefit. In fact, if the price of benzene continues to rise relative to the price of control equipment, it is merely a matter of time until many of the options become so attractive that firms will voluntarily employ them.

7.5.4 Impacts on Suppliers of Emissions Control Equipment

The primary concern in a regulatory action is usually confined to the industry being regulated. It is usually assumed that the rest of the economy is operating efficiently, and is sufficiently flexible to adjust to the changes in the regulated industry as easily as it adjusts to "normal" economic changes. However, when the relation of the regulated industry to some other industry is too close to ignore the adjustment effects in that other industry, it is necessary to expand the analysis. In this regard, the assumption made is that the industries supplying and being supplied by the producers and consumers of benzene are sufficiently flexible to adjust to the small changes estimated here for the petroleum and chemical industries, with one possible exception: the industry that supplies floating roofs for tanks. A requirement for contact internal floating roofs would increase demand faced by the firms which supply contact roofs, and the firms that cannot now produce such roofs would suffer a decrease in demand.

The decrease in demand faced by the sector of the industry that makes only noncontact roofs would be likely to decrease profits that the companies in that sector are able to make. The extent of the reduction in profit faced by the firm depends on two things: (1) the importance of benzene tank roofs relative to the overall output mix, and (2) the flexibility of the firm in rechanneling productive capacity into new lines. To the extent that benzene tank roofs represent a relatively small component of total sales, and to the extent that the capital and labor used in benzene tank roof manufacture can be used effectively in manufacturing other items, this aspect of the option merely serves to rechannel productive capacity, rather than cause economic hardship. Under certain circumstances, this rechannelling is just as equitable as the rechannelling of economic resources that comes about through the usual operation of the free market forces: supply, demand, and competition. The main difference is that in the free market case the economic forces are applied directly by the market participants shifting their demand from the old product to the new one with characteristics they prefer; however, because there is no market for clean air, shifts in market demands cannot be depended on to bring about economic changes. Instead, the individual demands of the people are collectively channelled through the government where they reach the producers through the enactment and enforcement of direct regulation. The only conditions needed to ensure that the actions of the government are equitable in the same sense that the operation of market forces is equitable, is that the article in demand have bonafide benefits over the existing product, and that the government is correctly interpreting the demands of the people.

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APPENDIX A
EVOLUTION OF THE BACKGROUND INFORMATION DOCUMENT

Table A-1. EVOLUTION OF THE BACKGROUND INFORMATION DOCUMENT

Date	Company, consultant or agency	Nature of action	Location
August 2, 1977	Shell Oil Company	Section 114 request for information	Durham, NC
August 2, 1977	Exxon Chemical Company U.S.A.	Section 114 request for information	Durham, NC
August 2, 1977	Sun Petroleum Products Company	Section 114 request for information	Durham, NC
August 2, 1977	Coastal States Petrochemical Company	Section 114 request for information	Durham, NC
August 2, 1977	Chevron U.S.A., Inc.	Section 114 request for information	Durham, NC
August 2, 1977	Atlantic Richfield Company	Section 114 request for information	Durham, NC
August 2, 1977	Gulf Oil Company, U.S.A.	Section 114 request for information	Durham, NC
August 2, 1977	Standard Oil Company (Indiana)	Section 114 request for information	Durham, NC
September 13, 1977	Exxon Chemical Company U.S.A. (Confidential)	Response to Section 114 letter	Houston, TX
September 14, 1977	Gulf Oil Company, U.S.A.	Response to Section 114 letter	Houston, TX
September 16, 1977	Chevron U.S.A., Inc.	Response to Section 114 letter	San Francisco, CA
September 23, 1977	Shell Oil Company	Response to Section 114 letter	Houston, TX

(continued)

Table A-1. Continued

Date	Company, consultant or agency	Nature of action	Location
September 23, 1977	Sun Petroleum Products Company	Response to Section 114 letter	Philadelphia, PA
September 27-28, 1977	Exxon Chemical Company U.S.A.	Plant visit	Baton Rouge, LA
September 29, 1977	Coastal States Petrochemical Company	Response to Sectin 114 letter	Corpus Christi, TX
November 22, 1977	Coastal States Petrochemical Company	Plant visit	Corpus Christi, TX
December 21, 1977	Standard Oil Company (Indiana)	Response to Section 114 letter	Chicago, IL
January 13, 1978	Atlantic Richfield Company	Response to Section 114 letter	Los Angeles, CA
September-December 1978	Chicago Bridge and Iron Company	Series of emissions tests on a pilot test tank storing benzene	Plainville, IL
November 2, 1978	Exxon Chemical Company U.S.A.	Plant visit	Baton Rouge, LA
December 14, 1978	Amerada Hess Corp.	Telephone survey of storage facilities	St. Croix, V.I.
December 14, 1978	American Hoechst Corp.	Telephone survey of storage facilities	Baton Rouge, LA

(continued)

Table A-1. Continued

Date	Company, consultant or agency	Nature of action	Location
December 14, 1978	American Petrofina, Inc.	Telephone survey of storage facilities	Big Spring, TX
December 14, 1978	Ashland Oil Company	Telephone survey of storage facilities	Neal, WV
December 14, 1978	Continental Oil Company	Telephone survey of storage facilities	Baltimore, MD
December 14, 1978	Colorado Fuel and Iron	Telephone survey of storage facilities	Pueblo, CO
December 14, 1978	Charter Oil Company	Telephone survey of storage facilities	Houston, TX
December 14, 1978	Cities Service Company	Telephone survey of storage facilities	Lake Charles, LA
December 14, 1978	Clark Oil and Refining	Telephone survey of storage facilities	Blue Island, IL
December 14, 1978	COS-MAR, Inc.	Telephone survey of storage facilities	Carville, LA
December 14, 1978	Crown Central Petroleum	Telephone survey of storage facilities	Pasadena, TX
December 14, 1978	El Paso Natural Gas	Telephone survey of storage facilities	Odessa, TX

(continued)

Table A-1. Continued

Date	Company, consultant or agency	Nature of action	Location
December 14, 1978	First Mississippi Corp.	Telephone survey of storage facilities	Pascaquola, MI
December 14, 1978	LTV Corporation	Telephone survey of storage facilities	Aliquippa, PA
December 14, 1978	Marathon Oil	Telephone survey of storage facilities	Texas City, TX
December 14, 1978	Mobay Chemical	Telephone survey of storage facilities	New Martinsville, WV
December 14, 1978	Monsanto Company	Telephone survey of storage facilities	Texas City, TX
December 14, 1978	Monsanto Company	Telephone survey of storage facilities	Sauget, TX
December 14, 1978	Monsanto Company	Telephone survey of storage facilities	St. Louis, MO
December 14, 1978	Montrose Chemical	Telephone survey of storage facilities	Henderson, NV
December 14, 1978	PPG Industries	Telephone survey of storage facilities	New Martinsville, WV
December 14, 1978	Quintana-Howell	Telephone survey of storage facilities	Corpus Christi, TX

(continued)

Table A-1. Continued

Date	Company, consultant or agency	Nature of action	Location
December 14, 1978	Reichold Chemical	Telephone survey of storage facilities	Morris, IL
December 14, 1978	Rubicon Chemicals	Telephone survey of storage facilities	Geismar, LA
December 14, 1978	Standard Chlorine	Telephone survey of storage facilities	Delaware City, DL
December 14, 1978	Tenneco, Inc.	Telephone survey of storage facilities	Chalmette, LA
December 14, 1978	Union Carbide	Telephone survey of storage facilities	Penuelas, P. R.
December 14, 1978	U. S. Steel	Telephone survey of storage facilities	Nelville Island, PA
December 14, 1978	U. S. Steel	Telephone survey of storage facilities	Geneva, VT
December 27, 1978	Exxon Chemical Company U.S.A.	Section 114 follow up letter	Durham, NC
December 27, 1978	Sun Petroleum Products Company	Section 114 follow up letter	Durham, NC
December 27, 1978	Coastal States Petrochemical Company	Section 114 follow up letter	Durham, NC

(continued)

Table A-1. Continued

Date	Company, consultant or agency	Nature of action	Location
December 27, 1978	Chevron U.S.A., Inc.	Section 114 follow up letter	Durham, NC
December 27, 1978	Atlantic Richfield Company	Section 114 follow up letter	Durham, NC
December 27, 1978	Gulf Oil Company, U.S.A.	Section 114 follow up letter	Durham, NC
December 27, 1978	Standard Oil Company (Indiana)	Section 114 follow up letter	Durham, NC
January 10, 1979	Standard Oil Company (Indiana)	Response to section 114 letter	Texas City, TX
January 11, 1979	Pittsburgh-Des Moines Steel Company	Telephone survey for cost information	Fullerton, CA
January 11, 1979	Brown Boiler and Tank Works	Telephone survey for cost information	Franklin, P
January 17, 1979	Tank Service, Inc.	Telephone survey for cost information	Tulsa, OK
January 17, 1979	Western Petroleum Chemical Services	Telephone survey for cost information	Los Angeles, CA
January 19, 1979	Exxon Chemical Company, U.S.A.	Response to Section 114 letter	Houston, TX
January 19, 1979	Chevron U.S.A., Inc.	Response to Section 114 letter	San Francisco, CA
January 25, 1979	Sun Petroleum Products Company	Response to Section 114 letter	Philadelphia, PA

(continued)

Table A-1. Continued

Date	Company, consultant or agency	Nature of action	Location
January 29, 1979	Gulf Oil Company	Response to Section 114 letter	Houston, TX
January 29, 1979	Shell Oil Company	Response to Section 114 letter	Houston, TX
January 30, 1979	Coastal States Petroleum Company	Response to Section 114 letter	Corpus Christi, TX
February 1, 1979	Phillips Petroleum	Plant visit	Sweeny, TX
March 13, 1979	Petrex, Inc.	Meeting with company representative	Durham, NC
June 1979	Chicago Bridge and Iron Company	Report submitted to EPA: Measurement of Benzene Emissions from a Floating Roof Test Tank	Plainville, IL
July 18, 1979	Beverly Chemical Terminal Company	Section 114 request for information	Durham, NC
July 18, 1979	Gordon Terminal Service Company	Section 114 request for information	Durham, NC
July 18, 1979	GATX Terminal Corp.	Section 114 request for information	Durham, NC
July 18, 1979	PetroUnited Terminals, Inc.	Section 114 request for information	Durham, NC
July 18, 1979	Amerada Hess Corp.	Section 114 request for information	Durham, NC
August 24, 1979	Gordon Terminal Service Company	Response to Section 114 letter	Bayonne, NJ

(continued)

Table A-1. Concluded

Date	Company, consultant or agency	Nature of action	Location
September 7, 1979	GATX Terminals Corp.	Response to Section 114 letter	Chicago, IL
September 20, 1979	PetroUnited Terminals, Inc.	Response to Section 114 letter	Seabrook, TX
October 11, 1979	Amerada Hess Corp. (Confidential)	Response to Section 114 letter	Woodbridge, NJ
April 17, 1980	EPA Public Hearing	NAPCTAC Committee Presentation	Raleigh, NC
May 16, 1980	San Diego Air Pollution Control District	Telephone survey to determine tank inspection procedure	San Diego, CA
June 6, 1980	Crown Central Refinery	Telephone survey of time required to empty tanks	Pasadena, CA
June 6, 1980	Mobay Chemical Co.	Telephone survey of time required to empty tanks	Natrium, WV
June 6, 1980	Texaco, Inc.	Telephone survey of time required to empty tanks	Port Arthur, TX
June 10, 1980	South Coast Air Quality Management District	Survey to determine inspection procedure on internal floating-roof tanks	Los Angeles, CA

APPENDIX B

INDEX TO ENVIRONMENTAL IMPACT CONSIDERATIONS

Table B-1. INDEX TO ENVIRONMENTAL IMPACT CONSIDERATIONS

Agency Guidelines for Preparing Regulatory Action Environmental Impact Statements (39 FR 37419)	Location within the Background Information Document
1. Background, description, and purpose of the regulatory alternatives and the statutory authority.	The regulatory alternatives from which standards will be chosen are summarized in Chapter 1, Section 1.1, as is the statutory authority for proposing standards.
The relationship to other actions and proposals significantly affected by the regulatory alternatives.	Other EPA regulations and to the extent possible, the OSHA regulations, which apply to the affected industries are included in the study of economic impact in Chapter 7.
Industry affected by the regulatory alternatives.	The industry and the emission sources within the industry affected by the regulatory alternatives are listed in Chapter 3.
Specific processes affected by the regulatory alternatives.	The specific processes and facilities affected by the regulatory alternatives are summarized in Chapter 3, Section 3.2.
Applicable control technologies	The control technologies which can be applied to reduce benzene emissions from storage tanks and the emission reductions which have been achieved by these control technologies are described in detail in Chapter 4.
2. Alternatives to the action.	The several categories of alternatives to the actions which were considered are listed below.
	a. Alternative regulatory approaches. The alternative approaches for regulating benzene emissions under Section 112 of the Clean Air Act and their advantages and disadvantages are outlined in Chapter 4.
	b. Alternative control devices. The alternative control devices which could be required by the regulatory alternatives and the reasons for selecting these particular alternatives are outlined in Chapter 4.

(continued)

Table B-1. Continued

Agency Guidelines for Preparing Regulatory Action Environmental Impact Statements (39 FR 37419)	Location within the Background Information Document
Agency's comparative evaluation of the beneficial and adverse environmental, health, social, and economic effects of each reasonable alternative.	a. A discussion of the Agency's comparative evaluation of the various alternative regulatory approaches for benzene emissions can be found in Chapter 5, Section 5.2. b. A summary of the beneficial and adverse environmental, health, social, and economic effects of the alternative levels of control can be found in Chapter 6. A detailed description of the economic impacts of each alternative control level, including the capital and annualized costs to the industry, can be found in Chapter 7, Section 7.2. The socio-economic impacts of the alternative control levels, including potential plant closures and maximum price increases in consumer products, can also be found in Chapter 7, Sections 7.4 and 7.5.
3. Environmental impact of the regulatory alternatives.	
a. Primary impact	
Primary impacts are those that can be attributed directly to the action, such as reduced levels of specific pollutants brought about by a new standard and the physical changes that occur in the various media with this reduction.	Air impact analysis shows the primary impacts in terms of model plants and for individual emission sources in Chapter 6, Section 6.2. Effects of alternative control levels on nationwide emissions are also discussed in Chapter 6, Section 6.2.

(continued)

Table B-1. Concluded

Agency Guidelines for Preparing Regulatory Action Environmental Impact Statements (39 FR 37419)	Location Within the Background Information Document
b. Secondary impact	
Secondary impacts are indirect or induced impacts. For example, mandatory reduction of specific pollutants brought about by a new standard could result in the adoption of control technology that exacerbates another pollution problem and would be a secondary impact.	Other environmental impacts of the individual controls which can be used to meet the regulatory alternatives are identified qualitatively in Chapter 6, Sections 6.2.3, 6.3, and 6.4. The secondary water impacts of the alternative control levels, are quantified in Chapter 6, Section 6.3. The energy consumption impact of the alternative control levels, is quantified in Chapter 6, Section 6.5.
4. Other considerations.	
a. Adverse impacts which cannot be avoided should a regulatory alternative be implemented.	A summary of the potential adverse environmental and health impacts of the regulatory alternatives and a discussion of the significance of each impact can be found in Chapter 6. Factors which already exist to eliminate some of the potential adverse impacts are identified. Those adverse impacts which cannot be avoided are also identified, along with any steps which can be taken to minimize them.
b. Irreversible and irretrievable commitments of resources which would be involved with the regulatory alternatives should one be implemented.	Irreversible and irretrievable resources which would be involved in the proposed action are discussed in Chapter 6, Section 6.6.1.

APPENDIX C

EMISSION SOURCE TEST DATA

-BENZENE STORAGE TANKS-

APPENDIX C – EMISSION SOURCE TEST DATA

C.1 INTRODUCTION

This appendix describes the emissions source test data obtained prior to and during the development of the Background Information Document (BID). The facilities tested are described, the test methods used are identified, and the data obtained presented.

C.2 ESTIMATING EMISSIONS FROM FLOATING-ROOF TANKS

The emissions from external and internal floating-roof tanks storing benzene were estimated in the BID using equations developed for EPA by the Chicago Bridge and Iron Company (CBI). This section summarizes the test methods, test results, and conclusions from this study.

C.2.1 Description of Test Facility

The benzene emissions test program was performed in a test tank at CBI's research facility in Plainfield, Illinois. The test tank was 20 feet in diameter and had a 9-foot shell height (see Figure C-1). The lower 5'-3" of the tank shell was provided with a heating/cooling jacket through which a heated or cooled water/ethylene glycol mixture was continuously circulated to control the product temperature.

The effect of wind blowing across the open top of a floating-roof tank was simulated by means of a blower connected to the tank by either a 30-inch or 12-inch diameter duct. An inlet plenum with rectangular openings was used to distribute the air entering the test tank shell. This air exited from the tank through a similar plenum into a 30-inch diameter exit duct. The 12-inch diameter air inlet duct was used for the internal floating roof simulation tests, and the 30-inch diameter inlet duct was used for the external floating roof simulation tests (which required larger air flow rates). While one size of inlet duct was in use, the other size was always closed.

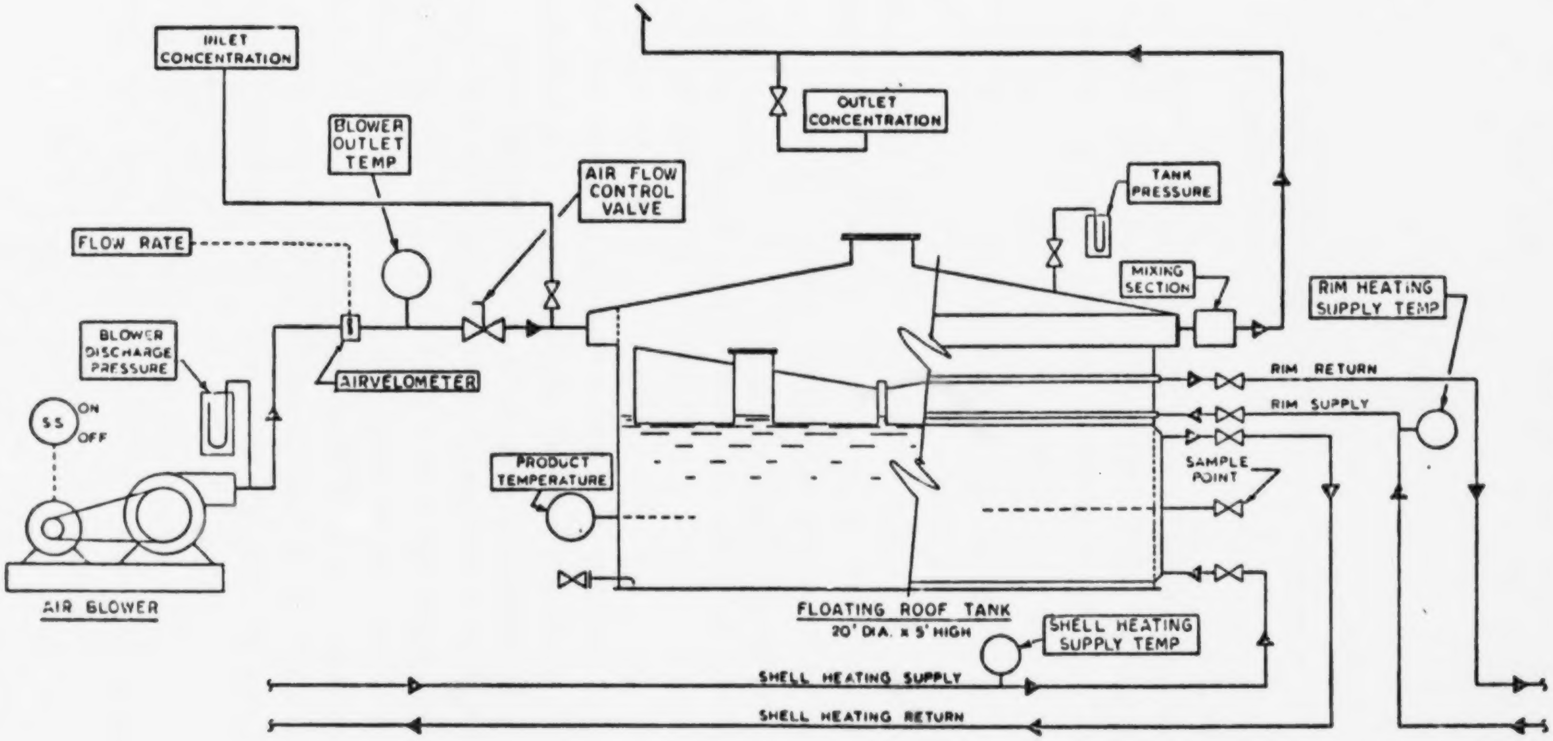

INLET CONCENTRATION
OUTLET CONCENTRATION
BLOWER OUTLET TEMP
AIR FLOW CONTROL VALVE
FLOW RATE
TANK PRESSURE
MIXING SECTION
RIM HEATING SUPPLY TEMP
BLOWER DISCHARGE PRESSURE
AIRVELOMETER
SS
ON
OFF
RIM RETURN
RIM SUPPLY
PRODUCT TEMPERATURE
SAMPLE POINT
AIR BLOWER
FLOATING ROOF TANK
20' DIA. x 5' HIGH
SHELL HEATING SUPPLY TEMP
SHELL HEATING SUPPLY
SHELL HEATING RETURN

Figure C-1. Simplified process and instrumentation schematic.

C.2.1.1 Principal Instrumentation. The principal instrumentation consisted of the following:

1. The air speed in the inlet duct was measured with a Flow Technology, Inc., air velometer, Model No. FTP-16H2000-GJS-12.
2. The total hydrocarbon concentrations were measured with Beckman Instruments, Inc., Model 400, total hydrocarbon analyzers. Two instruments were used, one for the inlet and one for the outlet.
3. The airborne benzene concentration at the test facility was measured with an HNU Systems, Inc., portable analyzer, Model PI 101.
4. The local barometric pressure was measured with a Fortin, Model 453, mercury barometer.
5. During unmanned periods (nights and weekends) the barometric pressure was measured with a Taylor Instruments, aneroid barometer, Weather-Hawk Stormoscope Barometex No. 6450.
6. The temperatures were measured with copper/constantan thermocouples and recorded with a multipoint potentiometer, Doric Scientific Corp., Digitrend, Model 210.

C.2.1.1.1 Analyzer calibration. Calibration gas mixtures were provided by Matheson Gas Products Company for the purpose of calibrating both the total hydrocarbon analyzers and the portable analyzer. Gas mixtures of three different benzene concentrations in ultra zero air were used:

0.894 ppmv
8.98 ppmv
88.6 ppmv

The inlet air analyzer and the portable analyzer were routinely calibrated with the 0.894 ppmv benzene calibration gas. The outlet air analyzer was calibrated with the gas mixture closest to the concentration currently being measured by the analyzer. Both total hydrocarbon analyzers were calibrated at the beginning of each 8-hour shift, and the portable analyzer was calibrated at least twice a week.

C.2.1.2 Product Description. The benzene used during the testing program was Nitration Grade Benzene as defined in ASTM-D-835-77.

C.2.2 Test Method

The testing was done in three phases, each using a different type of floating roof. Phase I used a contact-type internal floating roof. Phase II used a noncontact-type internal floating roof. Phase III used a double deck external floating roof.

A total of 29 tests were conducted during the three phases. Conditions were varied in order to determine the:

- Emissions from a tight primary seal.
- Emissions from a tight primary seal and secondary seal.
- Effect of gaps in the primary and/or the secondary seal.
- Contribution of deck fittings (penetrations) to emissions.
- Effect of vapor pressure (temperature) on emissions.

C.2.2.1 Description of Floating Roof and Seals.

C.2.2.1.1 Phase I, contact-type internal floating roof. A cross-sectional view of the position of the floating roof within the test tank is shown in Figure C-2.

A flapper secondary seal was used during some of the tests. This seal was 15 inches wide, with internal stainless steel reinforcing fingers. A sketch of its installation on the rim of the contact-type internal floating roof is shown in Figure C-3.

Description of test conditions--The test conditions for Phase I are summarized in Table C-1. This table presents a brief overview of the various temperatures, seal configurations, and deck fitting sealing conditions for the Phase I emissions tests.

C.2.2.1.2 Phase II, noncontact-type internal floating roof. The internal floating roof for the Phase II tests was fitted with shingled, flapper type primary and secondary seals. A plan view sketch of a portion of a shingle-type seal is shown in Figure C-4. Also, the dimensions of a single piece, or shingle, of the seal is shown. Figures C-5 and C-6 describe the details of the shingled, flapper type seal that was installed in lieu of the single continuous flapper seal used during the propane/octane tests. Figure C-5 shows a cross-sectional view of the position of the noncontact-type internal roof within the emissions test tank.

Description of test conditions--The description of test conditions for Phase II are summarized in Table C-2. This table presents a brief overview

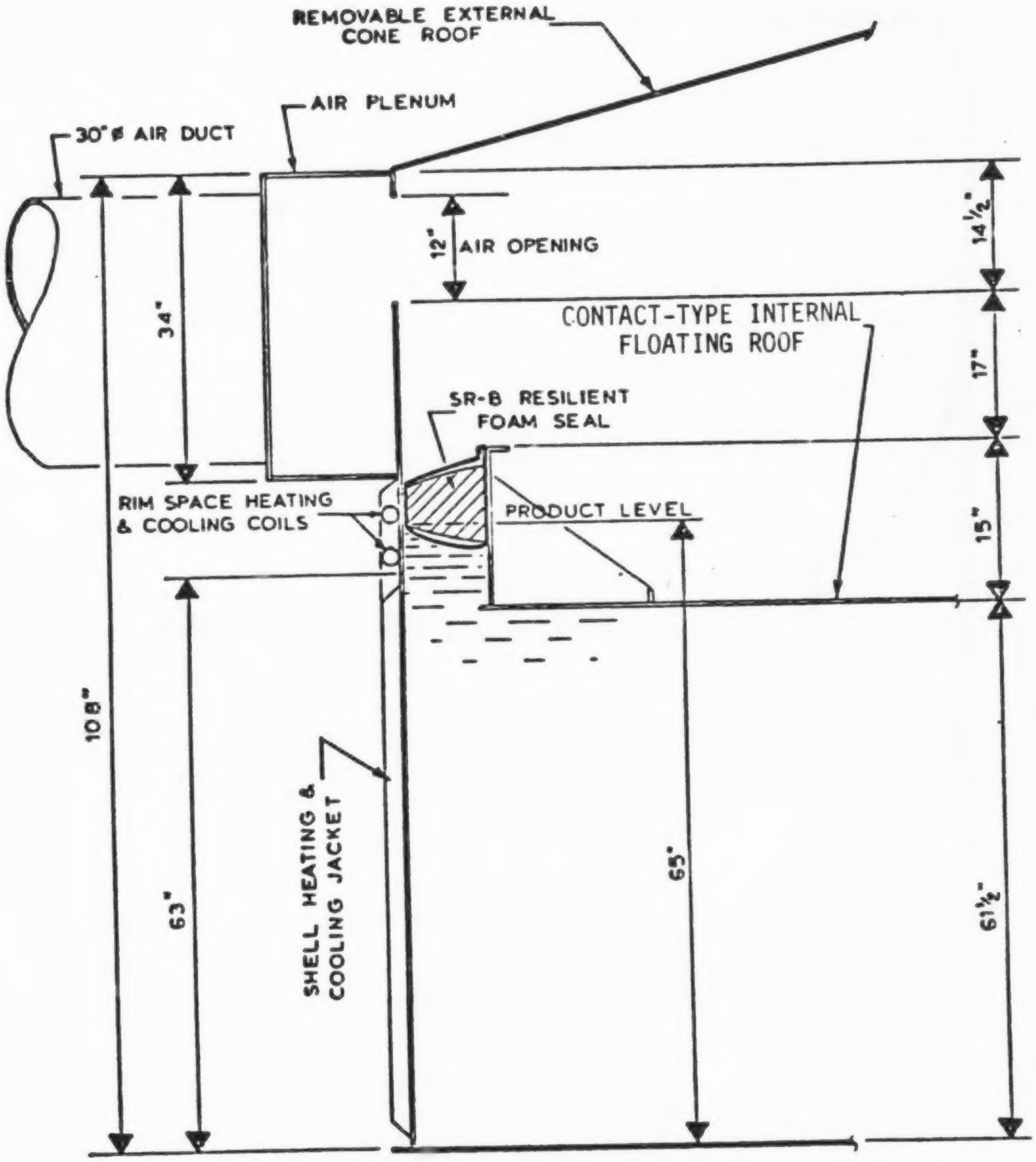

REMOVABLE EXTERNAL CONE ROOF
AIR PLENUM
30"ø AIR DUCT
12"
AIR OPENING
14½"
34"
CONTACT-TYPE INTERNAL FLOATING ROOF
17"
SR-B RESILIENT FOAM SEAL
RIM SPACE HEATING & COOLING COILS
PRODUCT LEVEL
15"
108"
63"
SHELL HEATING & COOLING JACKET
65"
61½"

Figure C-2. Position of the contact-type internal floating roof within the emissions test tank.

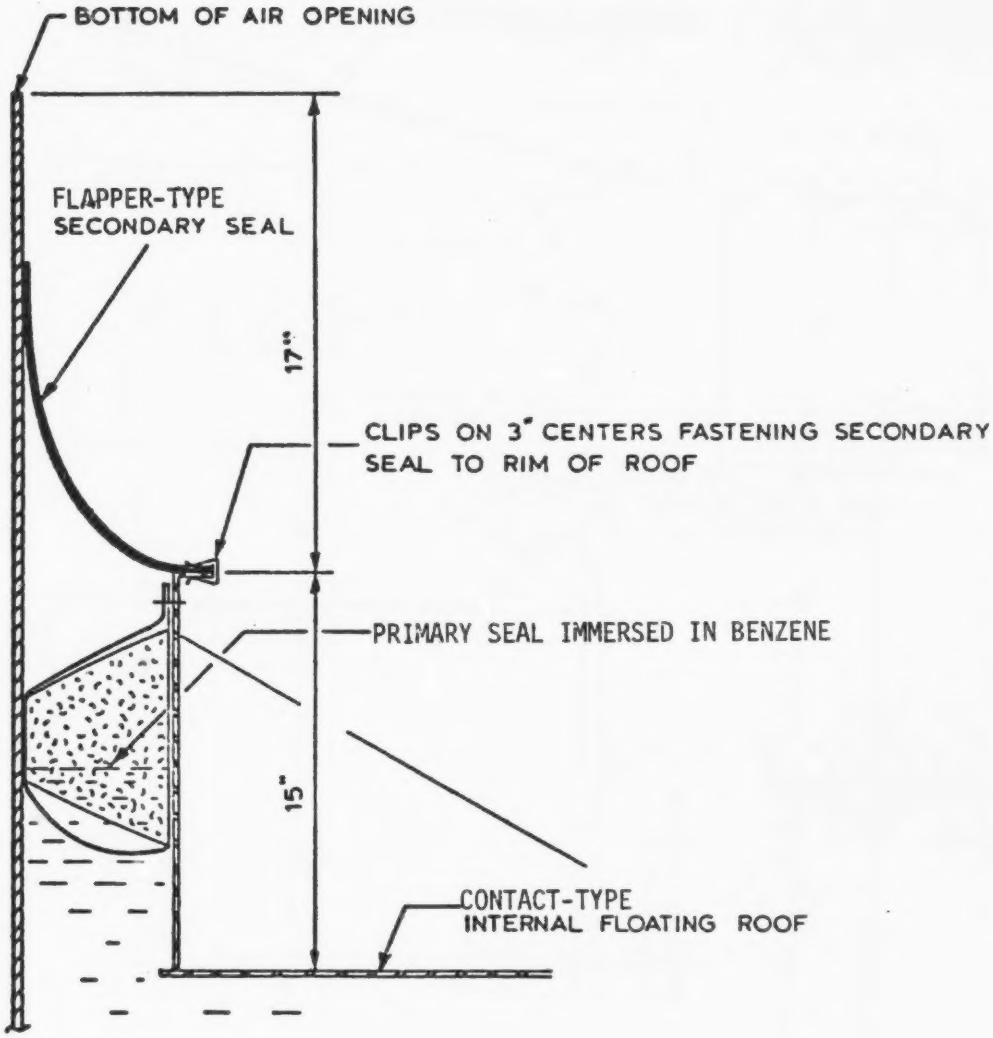
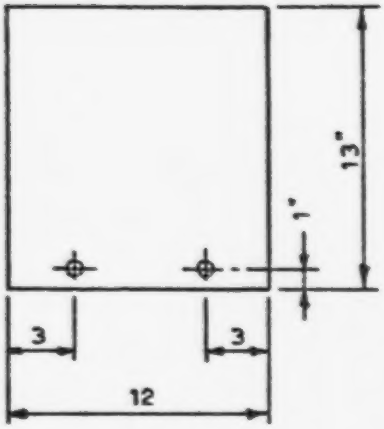

BOTTOM OF AIR OPENING
FLAPPER-TYPE SECONDARY SEAL
17"
CLIPS ON 3" CENTERS FASTENING SECONDARY SEAL TO RIM OF ROOF
PRIMARY SEAL IMMERSED IN BENZENE
15"
CONTACT-TYPE INTERNAL FLOATING ROOF

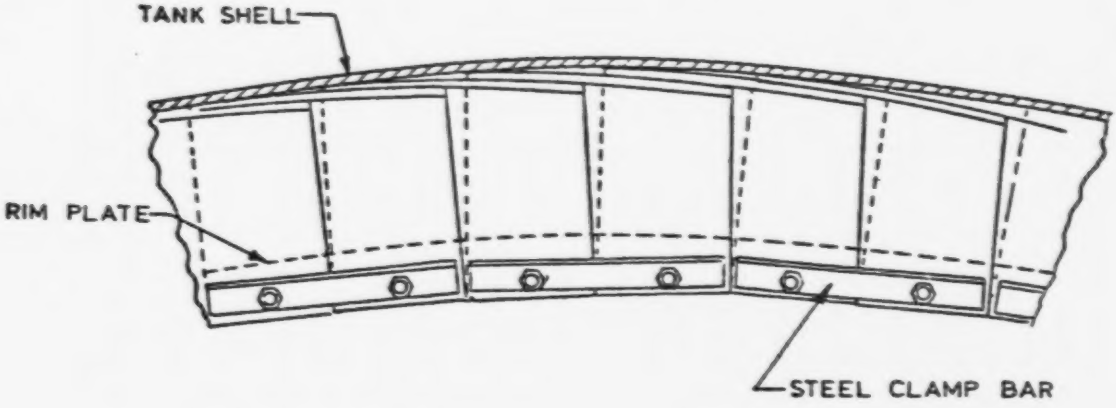
Figure C-3. Rim mounting of the flapper secondary seal.

Table C-1. SUMMARY OF TEST CONDITIONS FOR PHASE I, CONTACT-TYPE INTERNAL FLOATING ROOF

Test No.	Prod. Temp. (°F)	Primary Seal Gaps	Sec. Seal	Sec. Seal Gaps	Gage Hatch	Deck Fittings	Notes
EPA-1	80	None	None	None	Unsealed	Unsealed	Partial Test
EPA-2	80	None	None	None	Sealed	Unsealed	Partial Test
EPA-3	100	None	None	None	Sealed	Unsealed	Partial Test
EPA-4	100	None	None	None	Sealed	Sealed	Partial Test
EPA-5	100	None	None	None	Sealed	Sealed	
EPA-6	100	4-1½"x72"	None	None	Sealed	Sealed	
EPA-7	100	None	None	None	Unsealed	Unsealed	
EPA-8	80	None	None	None	Sealed	Sealed	
EPA-9	60	None	None	None	Sealed	Sealed	
EPA-10	75	None	Yes	None	Sealed	Sealed	Void Test
EPA-11	80	4-1½"x72"	None	None	Sealed	Sealed	
EPA-12	75	None	Yes	None	Sealed	Sealed	
EPA-13	75	4-1½"x72"	Yes	None	Sealed	Sealed	
EPA-14	75	4-1½"x72"	Yes	4-1½"x72"	Sealed	Sealed	
EPA-15	75	None	None	None	Sealed	Sealed	
EPA-16	75	2-½"x24"	None	None	Sealed	Sealed	



INDIVIDUAL PIECE OF SHINGLE-TYPE SEAL


TANK SHELL
RIM PLATE
STEEL CLAMP BAR

PLAN VIEW
(the same detail was used for both
primary and secondary seals)

Figure C-4. Installed shingle-type seal.

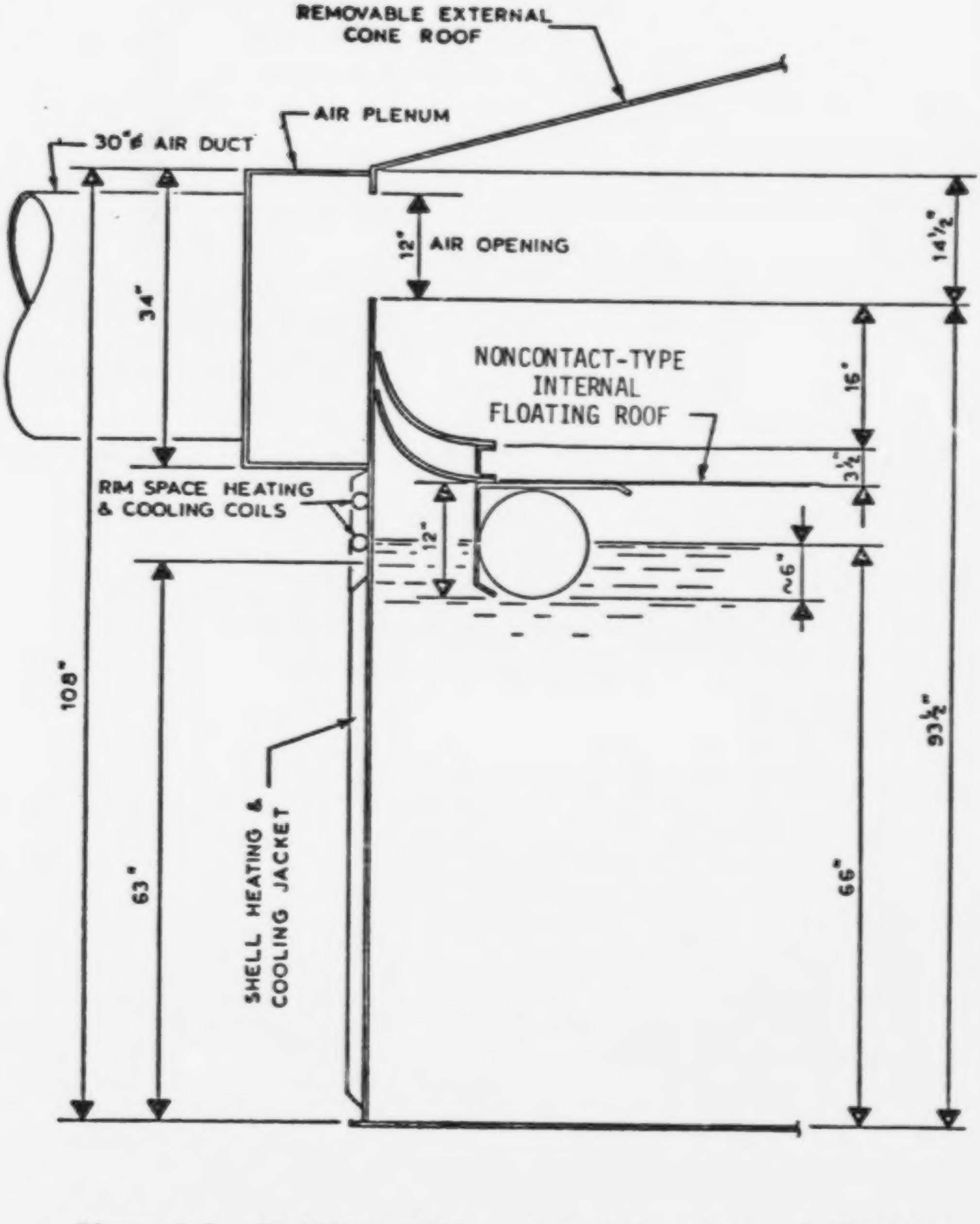

REMOVABLE EXTERNAL CONE ROOF
AIR PLENUM
30"ø AIR DUCT
12" AIR OPENING
14½"
34"
NONCONTACT-TYPE INTERNAL FLOATING ROOF
15"
3½"
RIM SPACE HEATING & COOLING COILS
12"
~6"
108"
63"
SHELL HEATING & COOLING JACKET
66"
93½"

Figure C-5. Position of the noncontact-type internal floating roof within the emissions test tank.

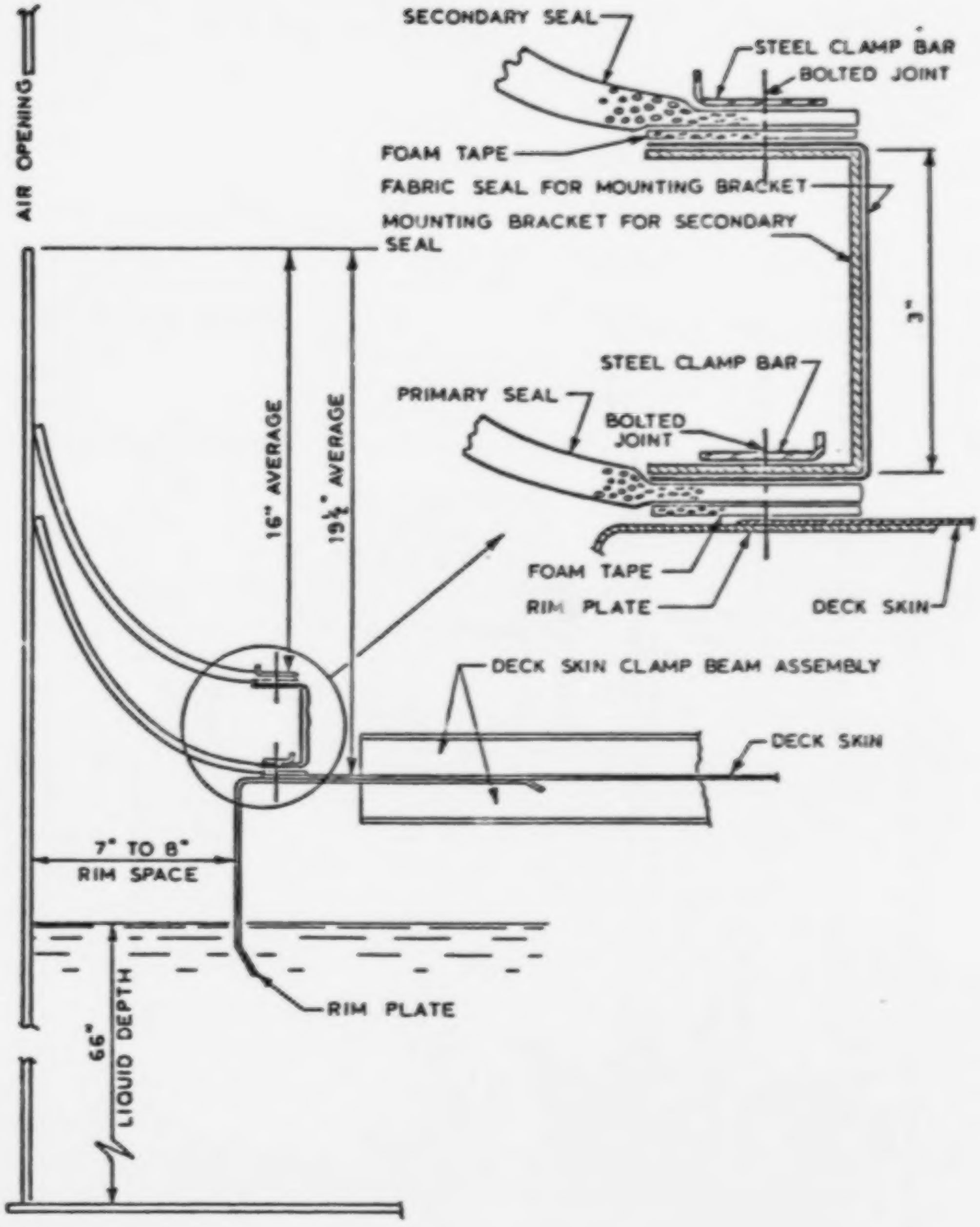

SECONDARY SEAL
STEEL CLAMP BAR
BOLTED JOINT
FOAM TAPE
FABRIC SEAL FOR MOUNTING BRACKET
MOUNTING BRACKET FOR SECONDARY SEAL
3"
STEEL CLAMP BAR
PRIMARY SEAL
BOLTED JOINT
FOAM TAPE
RIM PLATE
DECK SKIN
AIR OPENING
16" AVERAGE
19½" AVERAGE
DECK SKIN CLAMP BEAM ASSEMBLY
DECK SKIN
7" TO 8"
RIM SPACE
66"
LIQUID DEPTH
RIM PLATE

Figure C-6. Cross-sectional view of the shingle-type seal installation.

Table C-2. SUMMARY OF TEST CONDITIONS FOR PHASE II, NONCONTACT-TYPE INTERNAL FLOATING ROOF

Test No.	Product Temp. (°F)	Primary Seal Gaps	Sec. Seal	Sec. Seal Gaps	Deck Fittings	Notes
EPA-17	75	None	Yes	None	Sealed	
EPA-18	75	2-1/2"x24"	Yes	2-1/2"x24"	Sealed	
EPA-19	75	None	Yes	None	Sealed	Rim space temporarily sealed with plastic film.
EPA-20	75	None	Yes	None	Sealed	Rim space temporarily sealed with plastic film, and deck seams also sealed.
EPA-21	75	None	Yes	None	Sealed	Same conditions as EPA-20, but with additional sealing of deck seams.
EPA-22	75	None	Yes	None	Unsealed	Same conditions as EPA-21, but with all the temporary seals removed from the deck fittings.

of the various temperatures, seal configurations, and deck fitting sealing condition for the Phase II emissions tests.

C.2.2.1.3 Phase III, external double deck floating roof. A cross-sectional view of the position of the double deck roof within the test tank is shown in Figure C-7. The figure also illustrates the metallic shoe seal mounted on the double deck external floating roof. When a secondary seal was required, the flapper type secondary seal from Phase I was reused. However, in order to fit it to the double deck roof, the length of the secondary seal had to be shortened because of the slightly smaller diameter of the double deck roof.

Description of test conditions--The test conditions for Phase III are summarized in Table C-3. This table presents a brief overview of the various temperatures, seal configurations, and deck fitting sealing condition for the Phase III emissions tests.

C.2.3 Emissions Test Data

C.2.3.1 The Effect of Vapor Pressure on Emissions. Several emissions tests (EPA-5, EPA-9, and EPA-15) were initially conducted to determine the effect of the product vapor pressure, P, on the emissions rate. This relationship was evaluated during these tests by varying the product temperature in the pilot test tank which had been fitted with a contact-type internal floating roof and a liquid-mounted primary seal. The product temperatures maintained during the three respective tests were 100°F (EPA-5), 60°F (EPA-9), and 75°F (EPA-15). Based on these tests, the emissions are directly related to the vapor pressure function, f(P):

$$f(P) = \frac{\frac{P}{14.7}}{\left(1 + 1 - \left(\frac{P}{14.7}\right)^{0.5}\right)^{2}}$$

C.2.3.2 The Effect of Seal Gap Area on Emissions. Several tests were performed to determine the rates of emission as a function of seal gap area.

Table C-4 presents the seal gap areas tested and the measured emissions for the Phase I testing of a contact-type internal floating roof. Several conclusions are apparent from these tests:

1. A comparison of the emissions measured during tests EPA-5, EPA-9, and EPA-15 with the emissions measured during tests

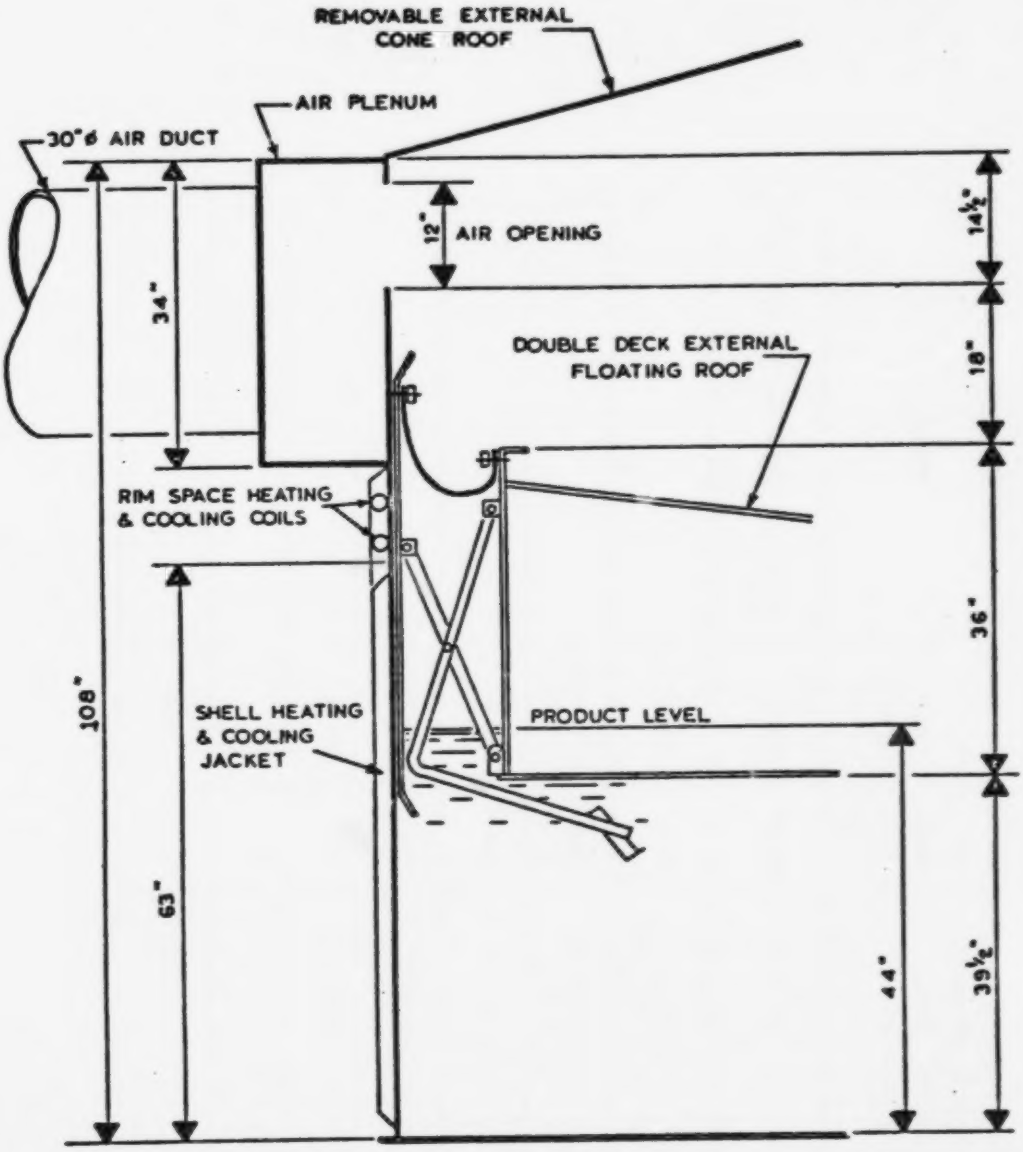

REMOVABLE EXTERNAL CONE ROOF
AIR PLENUM
30"ø AIR DUCT
12"
AIR OPENING
14½"
34"
18"
DOUBLE DECK EXTERNAL FLOATING ROOF
RIM SPACE HEATING & COOLING COILS
36"
108"
SHELL HEATING & COOLING JACKET
PRODUCT LEVEL
63"
44"
39½"

Figure C-7. Position of the double deck external floating roof within the emissions test tank.

Table C-3. SUMMARY OF TEST CONDITIONS FOR PHASE III, DOUBLE DECK EXTERNAL FLOATING ROOF

Test No.	Product Temp. (°F)	Primary Seal Gaps	Sec. Seal	Sec. Seal Gaps	Notes
EPA-23	75	None	None	None	Deck fittings sealed for all tests.
EPA-24	75	2-1"x24"	None	None	
EPA-25P	75	2-1"x24"	Yes	1-1 1/4"x 377"	
EPA-25	75	2-1"x24"	Yes	None	
EPA-26	75	2-1"x24"	Yes	2-1/2"x24"	
EPA-27	75	None	Yes	None	
EPA-28	75	4-1 1/2"x72"	Yes	2-1/2"x24"	
EPA-29	75	4-1 1/2"x72"	None	None	

Table C-4. MEASURED BENZENE EMISSIONS FROM EPA PHASE I TESTING, CONTACT-TYPE INTERNAL FLOATING ROOF

Test	Primary seal		Secondary seal		Emissions (lbs/day)		
	Number of gaps	Total gap size (in^2/ft)	Number of gaps	Total gap size (in^2/ft)	5 mph	10 mph	15 mph
EPA-5, EPA-9,[a] and EPA-15[a]	0	--	b	--	2.7	3.3	3.7
EPA-11	4	21	b	--	5.8	10.1	14.0
EPA-16	2	1.3	b	--	4.8	5.8	7.2
EPA-12	0	--	0	0	1.0	1.7	2.3
EPA-13	4	21	0	0	1.0	1.7	2.3

[a] Calculated as benzene at 1.75 psia TVP from the 20 foot diameter test tank.

[b] No secondary seal.

EPA-11 and EPA-16 clearly demonstrates that increasing gap areas in the primary seal increases emissions.

2. A comparison of the emissions measured during tests EPA-5, EPA-9, and EPA-15 with the emissions measured during test EPA-12, in addition to a comparison of the emissions measured during tests EPA-11 and EPA-13, demonstrates that the addition of a secondary seal reduces emissions.
3. A comparison of the emissions measured during tests EPA-12 and EPA-13 shows that, as long as the secondary seal has no gaps, the emissions rate is generally independent of the amount of gap in the primary seal.

No relationship between seal gap area and emissions could be established from the Phase II testing of a noncontact-type internal floating roof. This was probably a result of the type of primary and secondary seals used during the tests.

Table C-5 presents the seal gap areas and the measured emissions for the Phase III testing of a double deck external floating roof. Several conclusions are apparent from these tests:

1. A comparison of the emissions measured during tests EPA-23 and EPA-24 demonstrates that small gap areas in the primary seal do not increase emissions.
2. A comparison of the emissions measured during tests EPA-23 and EPA-27, in addition to a comparison of the emissions measured during tests EPA-24 and EPA-25, demonstrates that the addition of a secondary seal reduces emissions.
3. A comparison between similar cases in Tables C-4 and C-5 demonstrates that the emissions from an external floating-roof tank are much higher than the emissions from a contact-type internal floating-roof tank similarly equipped.

C.2.3.3 The Development of Seal Factors (K_s) and Wind Speed Exponents (n). The emission factors (K_s and n) for internal and external floating roofs with primary seals and primary and secondary seals were developed from the emissions tests data previously discussed. The emissions factors for contact internal floating roofs and external floating roofs having primary seals and primary and secondary seals are average

Table C-5. MEASURED BENZENE EMISSIONS FROM EPA PHASE III TESTING, DOUBLE DECK EXTERNAL FLOATING ROOF

Test	Primary seal		Secondary seal		Emissions (lbs/day)		
	Number of gaps	Total gap size (in^2/ft)	Number of gaps	Total gap size (in^2/ft)	5 mph	10 mph	15 mph
EPA-23	0	--	a	--	20	32	43
EPA-27	0	--	0	--	9.3	10.0	10.4
EPA-24	2	3.4	a	--	20	32	43
EPA-25	2	3.4	0	--	9.3	10.0	10.4
EPA-26	2	3.4	2	1.3	17.4	23	27

[a] No secondary seal.

seal factors developed from these test data and field tank gap measurement data. Using a methodology similar to one discussed in American Petroleum Institute (API) Publication 2517,[1] the test data from selected EPA Phase I and Phase III tests were weighted to represent gap measurement data collected by the California Air Resources Board (CARB) during seal gap area surveys on external floating roof tanks. Based on engineering judgment, it is reasonable to assume that they are also representative of the seal gaps on internal floating-roof tanks.

Consequently, the emission factors for a contact-type internal floating roof with a primary seal (cIFRps) were estimated based on the weighted average of tests EPA-15 and EPA-16, which have no measurable seal gap and 1.3 square inches of seal gap per foot of tank diameter, respectively. Because 65 percent of the tanks surveyed by CARB had no measurable gaps, the emissions measured during test EPA-15, the test with no measurable gap, were weighted at 65 percent. The remaining 35 percent was assigned to the emissions measured during test EPA-16.

Similarly, the emission factors for a contact-type internal floating roof with primary and secondary seals (cIFRss), an external floating roof with a primary seal (EFRps), and an external floating roof with primary and secondary seals (EFRss) were estimated by applying appropriate weighting factors to the EPA test data to represent the CARB tank survey data. Table C-6 summarizes the emission factors for internal and external floating roofs.

Some of the data collected during the Phase I and Phase III tests were not used to develop emission factors. Data collected during Phase I tests EPA-1 through EPA-4 were not used because these tests were performed primarly to evaluate the performance of the test facility. Data collected during test EPA-10 were voided because the secondary seal was not compatible with benzene. Data collected during test EPA-11 were not used because the seal gap area was unrealistically large.

Data collected during Phase III test EPA-25P were not used because of a failure of the secondary seal. Data collected during test EPA-28 were not used because the seal gap area was unrealistically large.

Additionally, while the testing did not specifically address the control effectiveness of placing a fixed roof over an external floating roof, it is reasonable to assume that the emissions from a tank so modified

Table C-6. EMISSION FACTORS AND THE BASIS OF ESTIMATION[2]

Roof and seal[a]	EPA test(s)	Primary seal gap (in²/ft tank diameter)	Secondary seal gap (in²/ft tank diameter)	Weighting factors, (%)	Emission Factors	
					K_S	n
cIFRps	EPA-15	0	no seal	65	12.7	0.4
	EPA-16	1.3	no seal	35		
cIFRss	EPA-13	21	0	90	3.6	0.7
	EPA-14	21	21	10		
ncIFRss	EPA-17,18	0, 1.3	0, 1.3	NA	10.3	1.0
EFRps	EPA-23	0	no seal	10	48.6	0.7
	EPA-24	3.4	no seal	85		
	EPA-29	14.4	no seal	5		
EFRss	EPA-25	3.4	0	75	57.7	0.2
	EPA-26	3.4	1.3	25		

[a] cIFRps - contact internal floating roof with a primary seal, cIFRss - contact internal floating roof with primary and secondary seals, ncIFRss - noncontact internal floating roof with primary and secondary seals, EFRps - external floating roof with a primary seal, EFRss - external floating roof with primary and secondary seals.

would be equivalent to the emissions from a contact internal floating-roof tank similarly equipped.

C.3 ESTIMATING EMISSIONS FROM FIXED-ROOF TANKS

As discussed in Chapter 3, the working and breathing loss equations from AP-42 were used to estimate benzene emissions from fixed-roof tanks storing benzene. However, breathing losses estimated using these equations were discounted by a factor of 4, based on recent fixed-roof tank tests conducted for the Western Oil and Gas Association (WOGA), EPA, and the German Society for Petroleum Science and Carbon Chemistry (DGMK).

C.3.1 WOGA and EPA Studies

During 1977 and 1978, 56 fixed-roof tanks were tested for WOGA and EPA. Fifty of these tanks, which were tested for WOGA, were located in Southern California and contained mostly California crudes, fuel oils, diesel and jet fuel. These tanks were in typical refinery, pipeline, and production service. The remaining six tanks, which were tested for EPA, contained isopropanol, ethanol, acetic acid, ethylbenzene, cyclohexane, and formaldehyde, respectively.

C.3.1.1 Test Methods for the WOGA and EPA Studies. The test methods for the WOGA and EPA studies followed the methods described in the American Petroleum Institute (API) Bulletin 2512, "Tentative Methods of Measuring Evaporative Loss from Petroleum Tanks and Transportation Equipment," Part II, Sections E and F. This document recommends that the emissions from a fixed-roof tank be estimated by measuring the hydrocarbon concentrations and flow rates leaving the tank.

In the WOGA study, the volume of vapors expelled from a tank was measured using a large and a small positive displacement diaphragm meter and a turbine meter connected in parallel. Three meters were used so that the potential range of flow rates could be covered. These meters were connected to the tank with flexible tubing. Vapor samples, which were taken from the tank using a heated sample line, were analyzed continuously with a total hydrocarbon analyzer. With continuous monitoring, fluctuations in the hydrocarbon concentration could be noted. Periodically, grab samples were taken and analyzed with a gas chromatograph, providing details on hydrocarbon speciation.

In the EPA study, the volume of vapor emitted from a tank was measured by positive displacement meters of either the bellows or rotary-type, depending on flow rate. Both meters were mounted so they could be manually switched for positive and negative flow through a one-way valve which was weighted, when applicable, to simulate the action of a pressure-vacuum valve. Vapors from the tank were sampled using a heated sample line (to reduce condensation in these lines), and then monitored with a total hydrocarbon analyzer calibrated specifically for the chemical in the tank. For the formaldehyde tank, a thermal conductivity gas chromatograph was used instead of a flame ionization detection gas chromatograph.

C.3.1.2 Test Data and Conclusions from the WOGA and EPA Studies. In these studies, 33 tank tests were available for correlation with the API 2518 breathing loss equation which is the basis for the breathing loss equation in AP-42. Table C-7 lists the emissions measured during each of these tests and the emissions calculated using the API equation. Measured versus calculated emissions for each of these tanks are also presented in Table C-7. Of the 33 tanks tested, only two had measured emissions larger than those calculated using the API breathing loss equation. In general, the API equation overestimated breathing losses by approximately a factor of 4.

An additional 13 tank tests from the WOGA study were available for evaluating the emissions from a fixed-roof tank in continuous working operation. However, because of limited and scattered data and the fact that breathing losses could not be separated out of the emissions, no suggestions were made for developing a new correlation for working losses from fixed-roof tanks.

C.3.2 DGMK Study

During 1974 and 1975, emissions tests were conducted by the German Society for Petroleum Science and Carbon Chemistry (DGMK) on a 3,000 cubic meter fixed-roof tank storing gasoline. The tests were designed to evaluate the effects of climate and method of operation on the emissions from the tank over a long period of time.

C.3.2.1 Test Methods for the DGMK Study. A large number of parameters were measured and recorded during the tests, including volume of vapor leaving the tank, concentration of hydrocarbons in the emitted vapor, gas pressure and temperature in the tank, liquid temperature, liquid level, ambient temperature, air pressure, and solar radiation. In addition,

Table C-7. MEASURED AND ESTIMATED BREATHING LOSSES FROM FIXED-ROOF TANKS

Test no.	Type of product	Measured breathing loss (bbl/yr)	API calculated breathing loss[a] (bbl/yr)	Measured/calculated
USEPA # 1	Isopropanol	20	59	0.34
2	Isopropanol	22	59	0.37
3	Ethanol	8	49	0.16
4	Ethanol	4	54	0.07
5	Ethanol	8	46	0.17
6	Acetic acid, glacial	24	75	0.32
7	Acetic acid, glacial	45	93	0.48
8	Ethyl benzene	15	39	0.38
9	Ethyl benzene	19	44	0.43
10	Cyclohexane	27	172	0.16
11	Cyclohexane	23	141	0.16
12	Cyclohexane	19	167	0.11
WOGA # 1	Crude	0	17	0.00
2	Crude	0	51	0.00
3	Fuel oil	0	91	0.00
4	Crude	0	10	0.00
5	Fuel oil	1	101	0.01
6	Diesel	0	21	0.00
7	Crude	224	607	0.37
8	Crude	164	257	0.64
9	Crude	222	856	0.26
10	Jet component	0	44	0.00

(continued)

Table C-7. Concluded

Test no.	Type of product	Measured breathing loss (bbl/yr)	API calculated breathing loss[a] (bbl/yr)	Measured/calculated
WOGA # 11	Crude	1	26	0.04
12	Crude	6	74	0.08
13	Crude	240	167	1.44
14	Fuel oil	3	17	0.18
15	Crude	84	138	0.61
16	Crude	339	490	0.69
17	Crude	1,086	783	1.39
18	Crude	0	61	0.00
19	Crude	9	298	0.03
20	Crude	0	2	0.00
21	Diesel	20	38	0.53
			Average	0.29

[a] API Bulletin 2518, "Evaporation Loss from Fixed-Roof Tanks."

using discontinuous measurements, vapor samples were analyzed in a laboratory for speciation and total hydrocarbons.

The flow rates from the tank were measured using three bellows gas counters connected to the breathing valves on the tank. Three gas counters were used so that extremely high and extremely low volume flows could be determined. The three bellows gas counters were installed on the roof of the tank. The pressure drop across the counters was 20 mm water column at full load. The additional pressure drop caused by the counters was compensated for by installing a new set of breathing valves.

An electrically-heated sampling line was connected from the outlet of each of the bellows gas counters to the measurement room. The vapors were analyzed with a flame ionization detector (FID) for total hydrocarbon content. Grab samples were also analyzed using two different gas chromatographic techniques to determine total hydrocarbons and individual components.

C.3.2.2 Test Data and Conclusions from the DGMK Study. Table C-8 presents the measured breathing and working losses and the losses calculated using the API 2518 breathing and working loss equations. A comparison of the measured and calculated losses indicates the measured breathing losses are only 24 percent of the estimated breathing losses. In addition, measured working losses are approximately 96 percent of the working losses estimated using API 2518.

Table C-8. COMPARISON OF MEASURED LOSSES WITH THOSE CALCULATED USING API 2518

Loss and time period	Measured (Mg)	Calculated[3] (Mg)	Measured/calculated (Mg)
Breathing loss[a]			
69 days	2.0	6.6	0.30
46 days	0.6	3.9	0.15
45 days	0.7	3.2	0.22
160 days (total)	3.3	13.2	0.24
Working loss			
69 days	12.2	12.2	1.0
46 days	11.3	12.9	0.88
45 days	5.9	5.6	1.05
160 days (total)	29.4	30.7	0.96

[a] Includes withdrawal loss.

C.4 REFERENCES FOR APPENDIX C

1. American Petroleum Institute. Evaporation Loss from External Floating-Roof Tanks. API Publication 2517. February 1980.

2. Letter and attachments from Moody, W. T., TRW, Incorporated, to Richard Burr, U.S. Environmental Protection Agency. April 24, 1980. Emission Factors for VOL and Benzene.

3. American Petroleum Institute. Evaporation Loss from Fixed-Roof Tanks. API Bulletin 2518. June 1962.

APPENDIX D

METHODOLOGY FOR ESTIMATING LEUKEMIA MORTALITY AND MAXIMUM LIFETIME RISK FROM EXPOSURE TO BENZENE EMISSIONS FROM BENZENE STORAGE TANKS

APPENDIX D – METHODOLOGY FOR ESTIMATING LEUKEMIA MORTALITY AND MAXIMUM LIFETIME RISK FROM EXPOSURE TO BENZENE EMISSIONS FROM BENZENE STORAGE TANKS

D.1 INTRODUCTION

The purpose of this appendix is to describe the methodology used in estimating leukemia mortality and maximum lifetime risk attributable to population exposure to benzene emissions from benzene storage tanks. The appendix is presented in three parts:

- Section D.2, Summary and Overview of Health Effects, summarizes and references reported health effects from benzene exposure. The major reported health effect is leukemia. Mortalities cited in the BID include only the estimated leukemia deaths attributable to exposure to benzene emissions from benzene storage tanks at existing petroleum refineries, chemical plants, and bulk storage terminals although other, sometimes fatal, effects are known to result from benzene exposure.

- Section D.3, Population Density Around Petroleum Refineries, Chemical Plants and Bulk Storage Terminals, describes the method used to estimate the population at risk; i.e., persons residing within 20 km of existing facilities having benzene storage tanks.

- Section D.4, Population Exposures, Mortalities, and Risks, describes the methodology for estimating benzene emissions from model plants, calculating expected population exposures, and estimating the number of leukemia deaths and maximum risk of leukemia attributable to benzene emissions from benzene storage tanks at 143 existing petroleum refineries, chemical plants, and bulk storage terminals.

D.2 SUMMARY AND OVERVIEW OF HEALTH EFFECTS

D.2.1 Health Effects Associated with Benzene Exposure

A large number of occupational studies over the past 50 years have provided evidence of severe health effects in humans from prolonged inhalation exposure to benzene. Some 300 studies[1] of the health effects of benzene have recently been reviewed and analyzed in terms of application to low-level ambient benzene exposures that might occur in a population residing near a source of benzene emissions.

The reviewers concluded that benzene exposure by inhalation is strongly implicated in three pathological conditions that may be of public health concern at environmental exposure levels:

- Leukemia (a cancer of the blood-forming system),
- Cytopenia (decreased levels of one or more of the formed elements in the circulating blood), and
- Chromosomal aberrations.

Leukemia is a neoplastic proliferation and accumulation of white blood cells in blood and bone marrow. The four main types are acute and chronic myelogenous leukemia and acute and chronic lymphocytic leukemia. The causal relationship between benzene exposure and acute myelogenous leukemia and its variants in humans appears established beyond reasonable doubt.[1]

The term "pancytopenia" refers to diminution of all formed elements of the blood and includes the individual cytopenias: anemia, leukopenia, thrombocytopenia, and aplastic anemia. In mild cases, symptoms of pancytopenia are such nonspecific complaints as lassitude, dizziness, malaise, and shortness of breath. In severe cases, hemorrhage may be observed, and death may occasionally occur because of hemorrhage or massive infection. Patients with pancytopenia may subsequently develop fatal, acute leukemia.

Chromosomal aberrations include chromosome breakage and rearrangement and the presence of abnormal cells. These aberrations may continue for long periods in hematopoietic and lymphoid cells. Ample evidence exists that benzene causes chromosomal aberrations in somatic cells of animals and humans exposed to benzene.[2] The health significance of these aberrations is not fully understood. However, aberrant cells have been observed in individuals exposed to benzene who have later developed leukemia. Some types of chromosomal aberrations may be heritable. Quantitative estimates of heritable genetic damage due to benzene cannot be made from data on the frequency of somatic mutations, although this damage may be occurring at concentrations as low as 1 ppm in air.

The review[1] concluded that man may be the only species yet observed to be susceptible to benzene-induced leukemia. Evidence for production of leukemia in animals by benzene injection was considered nonconclusive. Moreover, benzene exposure by oral dosing, skin painting, or inhalation has not been shown to produce leukemia or any other type of neoplastic diseases in test animals, although other effects, including pancytopenia, have been widely observed.

D.2.2 Benzene Exposure Limits

It should be noted that where the health effects described above have been associated with benzene exposure, the exposure has been at occupational levels. That is, the benzene exposure levels associated with the effects have been high (10 ppm up to hundreds of parts per million of benzene, except in a few cases of exposure to 2 to 3 ppm benzene) or they have been unknown.

Benzene exposure was first associated with health effects in occupational settings, so initial attempts to limit benzene exposures were aimed at occupational exposures. With recognition of the toxic effects of benzene and its greatly expanded use after 1920, several occupational exposure limits were established in the United States.[3] These limits, originally in the range of 75 to 100 ppm, were successively lowered as more information on benzene toxicity became known.

For example, the American Conference of Governmental Industrial Hygienists (ACGIH) recommended a benzene threshold limit value of 100 ppm in 1946, 50 ppm in 1947, 35 ppm in 1948, 25 ppm in 1949, and 10 ppm in 1977.[3,4] The National Institute for Occupational Safety and Health (NIOSH) recommended an exposure limit of 10 ppm in 1974 and revised it downward to 1 ppm in 1976.[5] The current Occupational Safety and Health Administration (OSHA) permissible exposure limit is 10 ppm[6].

Occupational exposure limits were initially established to protect workers from adverse changes in the blood and blood-forming tissues. The most recently recommended limit of 10 ppm is based on the conclusion that benzene is leukemogenic in man (NIOSH[5] and OSHA[7]) or a suspected carcinogen in man (ACGIH[4]).

The EPA Administrator announced in the June 8, 1977, Federal Register his decision to list benzene as a hazardous air pollutant under Section 112 of the Clean Air Act. A "hazardous air pollutant" is defined as an "air pollutant to which no ambient air quality standard is applicable and which . . . may reasonably be anticipated to result in an increase in mortality or an increase in serious irreversible, or incapacitating reversible illness."

D.2.3 Health Effects at Environmental Exposure Levels

Little information is available on the health effects of nonoccupational exposures of the general populace to benzene. Virtually all of the studies cited[1,2] were on the working population (mostly males) exposed to higher than ambient benzene levels on a work cycle. Applying these studies to chronic (24 hours per day) low-level exposure to the general population (including infants, the ill, and the elderly) requires extrapolation.

The recent analysis of benzene health effects[1] concluded that the evidence of increased risk of leukemia in humans on exposure to benzene for various time periods and concentrations was overwhelming but that the data were not adequate for deriving a dose-response curve.

However, EPA's Carcinogen Assessment Group (CAG), acknowledging the absence of a clear dose-response relationship, has estimated the risk of leukemia in the general population from low-level benzene exposure.[2] Data from three epidemiological studies of leukemia in workers (mostly adult white males) were used to estimate the risk of developing leukemia. The annual risk factor derived for benzene-induced leukemia was 0.34 deaths per year per 10^6 ppb-person years of exposure.

A nonthreshold linear model was used to extrapolate this estimated risk to the low levels (below 5 to 10 ppb) to which some populations may be exposed. For example, if 3 million persons are chronically exposed to 1 ppb benzene, the model predicts there will be 1.02 leukemia deaths (3 × 0.34) per year in that population. Use of a "linear" model means that the model would predict the same number of leukemia deaths among 3 million people exposed to 1 ppb benzene as among 1 million people exposed to 3 ppb.

The risk factor (0.34 deaths per year per 10^6 ppb-person years) was used in estimating the number of leukemia deaths attributable to benzene emissions from benzene storage tanks at petroleum refineries, chemical plants, and bulk storage terminals. Other effects of benzene exposure (including deaths from causes other than leukemia) were not included in the estimated number of deaths. The risk factor equated one leukemia case to one death (that is, each case was presumed fatal).

Several sources of uncertainty exist in applying the risk factor. First, the retrospective occupational exposure estimates may be inaccurate. CAG calculated the 95-percent confidence intervals for this risk factor to be 0.17 to 0.66 deaths per 10^6 ppb-person years if exposure estimates in the three studies extrapolated are precisely correct, and 0.13 to 0.90 if exposure estimates are within a factor of 2. Second, the composition of the exposed populations around petroleum refineries, chemical plants, and bulk storage terminals may vary from that of the populations used as a basis for the CAG estimate; the risk factor assumes that the susceptibility to leukemia associated with a cohort of white male workers is the same as that associated with the general population, which includes women, children, the aged, nonwhites, and the ill. Third, the true dose-response relationship for benzene exposure may not be a linear nonthreshold relationship at the low concentrations to which the general population may be exposed. Fourth, the risk factor includes only leukemia deaths and not other health risks. No quantitative estimate of the uncertainty in the risk factor due to the latter three factors has been attempted.

D.3 POPULATION DENSITY AROUND PETROLEUM REFINERIES, CHEMICAL PLANTS, AND BULK STORAGE TERMINALS

The population "at risk" to benzene exposure was considered to be persons residing within 20 km of facilities having benzene storage tanks. There are 143 such facilities in the United States: 28 large benzene producers, 34 small benzene producers, 77 benzene-consuming plants, and 4 bulk storage terminals. These facilities are referred to as "plants" in the ensuing discussion. Populations residing within radial distances of 1, 5, 10, and 20 km from each plant were estimated from an existing population file.[8] This file consists of a grid of 1-km^2 cells covering the continental United States, each with an assigned population. The population assigned to each cell was the 1975 estimated population, extrapolated from the 1960 and 1970 populations of the census enumeration district in which each cell occurs, assuming that the population is uniformly distributed within each of the 256,000 census enumeration districts. The population around each plant was determined by summing the populations of all cells occurring in annular areas at radial distances from the plant center of 0.5 to 1 km, 1 to 5 km, 5 to 10 km, and 10 to 20 km. The estimated total populations exposed as a function of distance from the plant site are reported in Reference 8, Table A-4.

There are some uncertainties in the above method. First, the assumption of uniform population distribution, both within enumeration districts and annular areas, may not be precisely correct. For urban areas the assumption is probably reasonably valid, but there is some uncertainty for rural areas 10 to 20 km from the site. Another area of uncertainty is the use of 1960 and 1970 population data. However, these are the latest available in the form required. No attempt was made to quantify the range of variability in the population figures.

D.4 POPULATION EXPOSURES, MORTALITIES, AND RISKS

D.4.1 Summary of Methodology for Calculating Deaths

The locations, descriptions, and capacities of all 143 U.S. plants known to have benzene storage tanks were compiled. Using these data as discussed in Chapter 3, four basic "model" plants were then developed to characterize the benzene storage facilities of large benzene producers, small benzene producers, benzene consumers, and bulk storage terminals. The model plants contain seven, four, two, and two benzene storage tanks, respectively, of various sizes. The benzene emissions rates from the various storage tanks were then estimated for the baseline using the available data. Each of the 143 existing plants was assigned the model most resembling it. All model plants were assumed to be located along the Texas-Louisiana Gulf Coast.

The omnidirectional annual average benzene concentrations (i.e., the concentrations estimated assuming that the wind blows equally from all directions) in ambient air resulting from benzene storage tank emissions were determined to a distance of 20 km from each model plant, according to the Industrial Source Complex (ISC) dispersion model, rural mode 1.[9] Lake Charles, Louisiana, meteorological data for the 1973-1976 period were used in the dispersion model. This period was considered representative of dispersion conditions in the areas where the majority of benzene plants are located.

The population around each actual plant location was then correlated with its modeled benzene concentrations to yield a benzene dose to that population in ppb-person years. The methods for determining populations are described in Section D.3 of this appendix.

From health effects data, the EPA Carcinogen Assessment Group[2] derived a leukemia risk estimate of 0.34 deaths per year per 10^6 ppb-person years from exposure to benzene. The methodology for estimating the leukemia risk factor is described in Section D.2.3 of this appendix.

The leukemia deaths per year attributable to exposure to benzene emissions from benzene storage tanks were estimated by multiplying 0.34×10^{-6} deaths per year per ppb-person year exposure times the exposure in "ppb-person years," as described in Section D.4.2. The leukemia deaths so calculated are summarized in Table D-1 for each plant, with a total for all plants of 0.31 deaths per year.

D.4.2 Estimates of Leukemia Deaths

The general equation for estimating the number of leukemia deaths attributable to benzene emissions from a particular plant (e.g., Plant X) is:[8]

$$\bar{D}_x = \sum_{i = 0.5-1.0}^{10-20} (R)(1/3.2)\,(2)(\pi)(p_i)(a)(D_{i_2}^{b+2} - D_{i_1}^{b+2})/(b+2)\ , \qquad (1)$$

where,

$\bar{D}_x$ = estimated number of leukemia deaths per year from benzene emissions from the plant (e.g., Plant X).

R = the risk factor (0.34 deaths per year per 10^6 ppb-person years).[2]

p_i = density of population at risk, in area (i) around Plant X.[8]

Table D-1. ESTIMATED LEUKEMIA DEATHS FROM BENZENE EMISSIONS FROM BENZENE STORAGE TANKS UNDER BASELINE CONDITIONS[a]

Plant code no.	Company (by region)	Location			Model[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
I. PRODUCERS						
Region II						
1	Exxon	NJ	Linden	Union	Pr. Sm.	0.008966
2	Texaco	NJ	Westville	Glouchester	Pr. Lge.	0.022872
3	Ashland Oil	NY	N. Tonawanda	Niagara	Pr. Sm.	0.000103
4	Commonwealth Oil	PR	Penuelas		Pr. Lge.	0.004243
5	Phillips	PR	Guayana		Pr. Lge.	0.004243
6	Amerada Hess	VI	St. Croix		Pr. Lge.	0.002504
Region III						
7	Getty	DE	Delaware City	New Castle	Pr. Sm.	0.000626
8	Gulf Oil	PA	Philadelphia	Philadelphia	Pr. Lge.	0.032803
9	Standard Oil	PA	Marcus Hook	Delaware	Pr. Sm.	0.003019
10	Sun Oil	PA	Marcus Hook	Delaware	Pr. Sm.	0.003019
Region IV						
11	Triangle Refineries	AL	Mobile	Mobile	Pr. Sm.	0.001552
12	Ashland Oil	KY	Catlettsburg	Boyd	Pr. Lge.	0.001295
13	Chevron	MS	Pascagoula	Jackson	Pr. Sm.	0.000584
Region V						
14	Shell Oil	IL	Wood River	Madison	Pr. Lge.	0.004407
15	Union Oil	IL	Lemont	Cook	Pr. Sm.	0.001643
16	Dow Chemical	MI	Bay City	Bay	Pr. Lge.	0.004242
17	Sun Oil	OH	Toledo	Lucas	Pr. Lge.	0.009912

(continued)

Table D-1. Continued

Plant code no.	Company (by region)	Location			Model[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
Region VI						
18	Cities Services	LA	Lake Charles	Calcasieu	Pr. Sm.	0.000330
19	Dow Chemical	LA	Plaquemine	Iberville	Pr. Lge.	0.000039
20	Exxon	LA	Baton Rouge	E. Baton Rouge	Pr. Lge.	0.007912
21	Gulf Oil	LA	Belle Chasse (Alliance)	Plaquemines	Pr. Lge.	0.000144
22	Pennzoil United	LA	Shreveport	Caddo	Pr. Lge.	0.008819
23	Tenneco	LA	Chalmette	St. Bernard	Pr. Sm.	0.002398
24	Union Carbide	LA	Taft	St. Charles	Pr. Lge.	0.000630
25	Sun Oil	OK	Tulsa	Tulsa	Pr. Sm.	0.001960
26	American Petrofina	TX	Port Arthur	Jefferson	Pr. Sm.	0.000637
27	Amoco (Standard)	TX	Texas City	Galveston	Pr. Lge.	0.003579
28	Atlantic Richfield	TX	Channelview	Harris	Pr. Lge.	0.004010
29	Atlantic Richfield	TX	Houston	Harris	Pr. Lge.	0.012060
30	Champlin	TX	Corpus Christi	Nueces	Pr. Sm.	0.001387
31	Charter International	TX	Houston	Harris	Pr. Sm.	0.005487
32	Coastal States	TX	Corpus Christi	Nueces	Pr. Lge.	0.001046
33	Cosden (American Petrofina)	TX	Big Spring	Howard	Pr. Lge.	0.000990
34	Crown Central	TX	Houston	Harris	Pr. Sm.	0.003415
35	Crown Central	TX	Pasadena	Harris	Pr. Sm.	0.003176
36	Dow Chemical	TX	Freeport	Brazoria	Pr. Lge.	0.000735
37	Exxon	TX	Baytown	Harris	Pr. Lge.	0.002872
38	Gulf Oil	TX	Port Arthur	Jefferson	Pr. Lge.	0.002123
39	Howell	TX	San Antonio	Bexar	Pr. Sm.	0.002722
40	Independent Refining	TX	Winnie	Chambers	Pr. Sm.	0.000074
41	Kerr-McGee	TX	Corpus Christi	Nueces	Pr. Sm.	0.001410
42	Marathon Oil	TX	Texas City	Galveston	Pr. Sm.	0.000869
43	Mobil Oil	TX	Beaumont	Jefferson	Pr. Lge.	0.004504
44	Monsanto	TX	Alvin	Brazoria	Pr. Lge.	0.000179

(continued)

Table D-1. Continued

Plant code no.	Company (by region)	Location			Model[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
Region VI (continued)						
45	Monsanto	TX	Texas City	Galveston	Pr. Lge.	0.002400
46	Phillips	TX	Borger	Hutchinson	Pr. Sm.	0.000198
47	Phillips	TX	Sweeny	Brazoria	Pr. Sm.	0.000070
48	Quintana Howell	TX	Corpus Christi	Nueces	Pr. Sm.	0.000952
49	Shell Oil	TX	Deer Park	Harris	Pr. Lge.	0.003791
50	Shell Oil	TX	Odessa	Ector	Pr. Sm.	0.000733
51	South Western	TX	Corpus Christi	Nueces	Pr. Sm.	0.001737
52	Suntide (Sun)	TX	Corpus Christi	Nueces	Pr. Lge.	0.001644
53	Texaco	TX	Port Arthur	Jefferson	Pr. Lge.	0.003834
54	Union Pacific	TX	Corpus Christi	Nueces	Pr. Sm.	0.001737
55	Union 76	TX	Nederland	Jefferson	Pr. Sm.	0.000881
Region VII						
56	Getty	KS	El Dorado	Butler	Pr. Sm.	0.000252
Region IX						
57	Atlantic Richfield	CA	Carson (Wilmington)	Los Angeles	Pr. Sm.	0.000339
58	Arco	CA	Long Beach	Los Angeles	Pr. Sm.	0.006385
59	Chevron (Standard)	CA	El Segundo	Los Angeles	Pr. Sm.	0.005977
60	Chevron (Standard)	CA	Richmond	Contra Costa	Pr. Sm.	0.002491
61	Hawaiian Independent	HI	Honolulu	Honolulu	Pr. Sm.	0.006016
62	Standard Oil	HI	Honolulu	Honolulu	Pr. Sm.	0.006016
II. CONSUMERS						
Region II						
63	American Cyanamid	NJ	Bound Brook	Somerset	Cons.	0.001174
64	DuPont	NJ	Gibbstown	Glouchester	Cons.	0.002153

(continued)

Table D-1. Continued

Plant code no.	Company (by region)	Location			Model[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
Region II (continued)						
65	Exxon	NJ	Linden	Union	Cons.	0.004446
66	Hummel Chemical	NJ	S. Plainfield	Middlesex	Cons.	0.002180
67	Reichhold	NJ	Elizabeth	Union	Cons.	0.005169
68	Standard Chlorine Chemical	NJ	Kearney	Hudson	Cons.	0.008411
69	Tenneco	NJ	Fords	Middlesex	Cons.	0.002060
70	Texaco	NJ	Westville	Glouchester	Cons.	0.003294
71	Allied Chemical	NY	Syracuse	Onondaga	Cons.	0.001831
72	ICC Industries	NY	Niagara Falls	Niagara	Cons.	0.000962
73	Commonwealth Oil	PR	Penuelas		Cons.	0.000607
74	Corco Refining	PR	Talluboa Penuelas	Guayanilla	Cons.	0.000607
75	Phillips	PR	Guayana		Cons.	0.000607
76	Union Carbide	PR	Penuelas		Cons.	0.000607
Region III						
77	Standard Chlorine	DE	Delaware City	New Castle	Cons.	0.000392
78	Continental Oil	MD	Baltimore	Baltimore	Cons.	0.002694
79	Atlantic Richfield	PA	Beaver Valley	Beaver	Cons.	0.000574
80	Gulf Oil	PA	Philadelphia	Phildelphia	Cons.	0.004697
81	Koppers	PA	Bridgeville	Allegheny	Cons.	0.002295
82	Allied Chemical	WV	Moundsville	Marshall	Cons.	0.000250
83	American Cyanamid	WV	Willow Island	Pleasants	Cons.	0.000106
84	Ashland Oil	WV	Neal	Wayne	Cons.	0.000187
85	Mobil	WV	Martinsville	Wetzel	Cons.	0.000085
86	PPG Industries	WV	New Martinsville	Wetzel	Cons.	0.000079
87	Union Carbide	WV	Charleston	Kanawha	Cons.	0.000432
Region IV						
88	Reichhold	AL	Holt	Tuscaloosa	Cons.	0.000184

(continued)

Table D-1. Continued

Plant code no.	Company (by region)	Location			Model[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
Region IV (continued)						
89	Ashland Oil	KY	Catlettsburg	Boyd	Cons.	0.000262
90	B. F. Goodrich	KY	Calvert City	Marshall	Cons.	0.000043
91	G.A.F.	KY	Calvert City	Marshall	Cons.	0.000042
92	Olin Corporation	KY	Brandenburg	Meade	Cons.	0.000058
93	First Mississippi	MS	Pascagoula	Jackson	Cons.	0.000264
Region V						
94	Clark Oil	IL	Blue Island	Cook	Cons.	0.000704
95	Monsanto	IL	Sauget	St. Clair	Cons.	0.002812
96	Reichhold Chemical	IL	East Morris	Grundy	Cons.	0.000095
97	Dow Chemical	MI	Bay City	Bay	Cons.	0.000594
98	Dow Chemical	MI	Midland	Midland	Cons.	0.000398
Region VI						
99	Transvaal	AR	Jacksonville	Pulaski	Cons.	0.000310
100	American Hoechst	LA	Baton Rouge	E. Baton Rouge	Cons.	0.001011
101	COS-MAR	LA	Carville	Iberville	Cons.	0.000095
102	Gulf Oil	LA	Donaldsonville	Ascension	Cons.	0.000109
103	Gulf Oil	LA	Welcome	St. James	Cons.	0.000062
104	Rubicon Chemicals	LA	Geismar	Ascension	Cons.	0.000090
105	Sun Company	OK	Tulsa	Tulsa	Cons.	0.000966
106	Amoco (Standard)	TX	Texas City	Galveston	Cons.	0.000504
107	Atlantic Richfield	TX	Port Arthur	Jefferson	Cons.	0.000414
108	Celanese	TX	Clear Lake	Harris	Cons.	0.000340
109	Celanese	TX	Pampa	Gray	Cons.	0.000218
110	Coastal States	TX	Corpus Christi	Nueces	Cons.	0.000149
111	Cosden (American Petrofina)	TX	Big Spring	Howard	Cons.	0.000140
112	DENKA (Petrotex)	TX	Houston	Harris	Cons.	0.001920

(continued)

Table D-1. Continued

Plant code no.	Company (by region)	Location			Model[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
Region VI (continued)						
113	Dow Chemical	TX	Freeport	Brazoria	Cons.	0.000104
114	DuPont	TX	Beaumont	Jefferson	Cons.	0.000344
115	El Paso Natural Gas	TX	Odessa	Ector	Cons.	0.000417
116	Exxon	TX	Baytown	Harris	Cons.	0.000410
117	Gulf Oil	TX	Port Arthur	Jefferson	Cons.	0.000301
118	Marathon Oil	TX	Texas City	Galveston	Cons.	0.000426
119	Mobil Oil	TX	Beaumont	Jefferson	Cons.	0.000635
120	Monsanto	TX	Chocolate Bayou	Brazoria	Cons.	0.000026
121	Monsanto	TX	Texas City	Galveston	Cons.	0.000339
122	Oxirane	TX	Channelview	Harris	Cons.	0.000577
123	Petrotex Chemical	TX	Houston	Harris	Cons.	0.001920
124	Phillips	TX	Sweeny	Brazoria	Cons.	0.000035
125	Standard Oil	TX	Texas City	Galveston	Cons.	0.000504
126	Suntide (Sun)	TX	Corpus Christi	Nueces	Cons.	0.000237
127	Texaco	TX	Port Arthur	Jefferson	Cons.	0.000539
128	Texas Eastman	TX	Longview	Gregg	Cons.	0.000177
129	Union Carbide	TX	Seadrift	Calhoun	Cons.	0.000017
130	Union Pacific	TX	Corpus Christi	Nueces	Cons.	0.000851
131	Union 76	TX	Nederland	Jefferson	Cons.	0.000434
Region VII						
132	Getty	KS	El Dorado	Butler	Cons.	0.000123
133	Monsanto	MO	St. Louis	St. Louis	Cons.	0.004355
Region IX						
134	Chevron	CA	El Segundo	Los Angeles	Cons.	0.002971
135	Chevron	CA	Richmond	Contra Costa	Cons.	0.001141
136	Diamond Shamrock	CA	Redwood City	San Mateo	Cons.	0.000008
137	Specialty Organics	CA	Irwindale	Los Angeles	Cons.	0.002555

(continued)

Table D-1. Concluded

Plant code no.	Company (by region)	Location			Model[a]	Leukemia deaths per year from benzene exposure[b]
		State	City	County		
Region IX (continued)						
138	Witco Chemical	CA	Los Angeles (Carson)	Los Angeles	Cons.	0.000906
139	Montrose Chemical	NJ	Henderson	Clark	Cons.	0.000317
III. BULK STORAGE TERMINALS						
Region III						
140	Gordon Terminal Services, Inc.	PA	McKees Rock	Allegheny	BST	0.002807
Region VI						
141	Amerada Hess Corp.	TX	Houston	Harris	BST	0.002037
142	GATX Terminal Corp.	TX	Houston	Harris	BST	0.001920
143	Petrounited Terminals, Inc.	TX	Seabrook	Harris	BST	0.000271
					TOTAL DEATHS	0.310380[c,d]

Footnotes for Table D-1 are on the next page.

FOOTNOTES FOR TABLE D-1

[a] Model used to estimate benzene concentrations around plant. The models are designated as follows:
Pr. Lge. = large benzene producer, Pr. Sm. = small benzene producer, Cons. = benzene consumer,
BST = bulk storage terminal.

[b] Confidence limits of 95 percent are obtained by multiplying and dividing figures shown by 2.64. This results in a 95 percent confidence interval that assumes the estimated concentrations to which the workers were exposed, as discussed in the CAG report,[2] are within a factor of 2.

[c] Total may not be exact past three decimal places due to rounding.

[d] It should be recognized that considerable uncertainty is associated with the cases of leukemia that appear in the table. First, the cases were calculated based on an extrapolation of leukemia risk associated with a healthy white male cohort of workers to the general population, which includes men, women, children, infants, the aged, nonwhites, and the unhealthy. Second, there are uncertainties in estimating the benzene levels to which people in the vicinity of petroleum refineries, chemical plants, and bulk storage terminals are exposed. Also, the number of cases includes consideration of only one effect of benzene exposure; i.e., leukemia. Benzene exposure has also been indicated to cause aplastic anemia, cytopenias, and the development of chromosomal aberrations. In addition, the benefits to the general population of controlling other hydrocarbon emissions from petroleum refineries, chemical plants, and bulk storage terminals are not quantified.

D_{i_2} and D_{i_1} = distances from plant to outer edge (D_{i_2}) and inner edge (D_{i_1}) of area i (e.g., for the area 5-10 km from the plant, D_{i_2} = 10 km and D_{i_1} = 5 km).

(1/3.2) = factor converting µg/m³ to ppb, the units in which R is expressed.

a and b = values describing the dispersion pattern of benzene in air around Plant X, according to the equation $B_i = a\,D_i^b$, in which B_i is the benzene concentration at distance D_i from the plant. Values of a and b are unique to each annular area i around each model plant.

i = the particular area in which p_i occurs (i progresses from the area 0.5 to 1.0 km from the plant to the area 10 to 20 km from the plant).

Σ = summation of deaths per year from all areas (i).

This equation is a mathematically rigorous method for estimating the exposure to the population within any area between D_{i_1} and D_{i_2} km from the plant, taking into account that with constant population density (p_i) more people reside near the outer edge of the area than near the inner edge, and that the benzene concentration (B_i) decreases with distance from the plant. The equation is derived in Reference 8.

Values of a and b were calculated for each annular area associated with each model plant as follows:

$$b = \frac{\ln(B_{i_2}/B_{i_1})}{\ln(D_{i_2}/D_{i_1})} \tag{2}$$

$$a = B_{i_2}/(D_{i_2})^b \tag{3}$$

in which B_{i_1} is the benzene concentration at the inner edge of area i (i.e., at distance D_{i_1}), and B_{i_2} is the omnidirectional annual average benzene concentration at the outer edge of area i (i.e., at distance D_{i_2}). B_i values for each distance (D_i) from each model plant are listed in Reference 9.

Population density (p_i) for a particular annular area around a particular plant is obtained by dividing the total population in that area (P_i) by the area in square kilometers; i.e.:

$$p_i = P_i/[\pi(D_{i_2}^2 - D_{i_1}^2)] \quad . \tag{4}$$

P_i values for each plant and annular area are listed in Reference 8. In summary, for each annular space around a particular plant, the P_i, D_{i_2}, and D_{i_1} values are taken from Reference 8. B_i values at all distances (D_i) are taken from Reference 9. Values of b, a, and p_i are calculated from Equations 2, 3, and 4, respectively, for each annular area. Then, using Equation 1, exposures in μg/m³-person years are calculated for each annular area, divided by 3.2 to convert μg/m³ to ppb, the units in which R is expressed, and multiplied by R to yield the number of deaths in each annular area. These deaths are summed to give $\bar{D}_x$, the annual leukemia deaths attributable to benzene emissions from Plant X.

The total estimated number of leukemia deaths per year attributable to benzene emissions from all plants was determined by the equation:

$$\text{Total estimated number of leukemia deaths/yr } (\bar{D}_t) = \bar{D}_1 + \bar{D}_2 + \ldots + \bar{D}_{143} \quad . \tag{5}$$

The total numbers of estimated leukemia deaths attributable to benzene emissions from existing benzene storage tanks are given in the last column of Table D-1 on a plant-by-plant basis, in deaths per year, assuming the baseline is effective as discussed in Section 3.3.1.1. The number of deaths expected under each of the control options can also be derived using the same methodology.

D.4.3 Example of Leukemia Death Calculation

Plant no. 4 from Table D-1 was chosen for an example calculation of the number of leukemia deaths attributable to benzene emissions from benzene storage tanks. For a determination of the number of deaths according to Equation 1, numerical values are needed for R, a, p_i, D_{i_2}, D_{i_1}, and b. In turn, for a determination of p_i from Equation 4, the numerical value of P_i for each annular area must be known. For a determination of b and a from Equation 2 and Equation 3, respectively, numerical values of ${}^{B}i_{1}$ and ${}^{B}i_{2}$ must be known for each distance.

Calculations are shown in Table D-2. The values in the first three lines of Table D-2 are common to all plants. They show the distances at which concentrations and populations were measured and the risk factor (R). Line 4 shows the population (P_i) in each annular ring, obtained from Table A-4, Reference 8, for Plant 4.

Lines 5 and 6 show the benzene concentrations at various distances from the plant for the applicable model. These are found as follows: Table A-1, Reference 8, indicates that the "large producer" model plant applies to Plant no. 4. Table B-1, Reference 9, indicates the omnidirectional annual average benzene concentrations by distance for this model. Note that concentrations for 1, 5, and 10 km from the plant apply to the outer edge (${}^{B}i_{2}$) of one ring and the inner edge (${}^{B}i_{1}$) of the adjacent ring.

Lines 7 through 11 show the calculations. These are shown below for the outer ring. From Equation 4:

$$p_i = P_i/[\pi({}^{D}i_2^2 - {}^{D}i_1^2)] = 287{,}456/[\pi(20^2 - 10^2)] = 305.0$$

From Equation 2:

$$b = \ln({}^{B}i_2/{}^{B}i_1)/\ln({}^{D}i_2/{}^{D}i_1) = \ln(0.0342/0.0903)/\ln(20/10) = -1.401$$

From Equation 3:

$$a = {}^{B}i_2/\left({}^{D}i_2\right)^{b} = 0.0342/(20)^{-1.401} = 2.27$$

All the values needed for using Equation 1 are now available, so:

Deaths for 10- to 20-km ring $D_{10-20} = (R/3.2)2\pi p_i a({}^{D}i_2^{b+2} - {}^{D}i_1^{b+2})/(b+2)$,

$\bar{D}_{10-20} = (0.34 \times 10^{-6}/3.2)2\pi(305.0)(2.27)(20^{0.599} - 10^{0.599})/0.599$, and

$\bar{D}_{10-20} = 0.001580$

Table D-2. EXAMPLE CALCULATION OF LEUKEMIA DEATHS, PLANT 4

Line no.	Factor	Annular ring around plant (km) 0.1-1	1-5	5-10	10-20	Source of data
	GIVEN DATA					
1	Distance to outer ring edge, D_{i_2}(km)	1	5	10	20	Refs. 8, 9
2	Distance to inner ring edge, D_{i_1}(km)	0.1	1	5	10	Refs. 8, 9
3	R, risk factor (deaths/ppb-person yr)	0.34×10^{-6}	0.34×10^{-6}	0.34×10^{-6}	0.34×10^{-6}	Ref. 2
4	Population in annular ring (persons)	720	22,996	71,864	287,456	Ref. 8, Table A-4 for Plant 4
5	Benzene conc. at outer ring edge, B_{i_2}($\mu g/m^3$)	2.66	0.246	0.0903	0.0342	Ref. 9, Table B-1 for Model Pr. Lge.[a]
6	Benzene conc. at inner ring edge, B_{i_1}($\mu g/m^3$) B	10.4	2.66	0.246	0.0903	Ref. 9, Table B-1 for Model Pr. Lge.[a]
	CALCULATIONS					
7	Population density, p_i (persons/km^2) $p_i = P_i/[\pi(D_{i_2}^2 - D_{i_1}^2)]$	305.6[b]	305.0	305.0	305.0	Equation 4
8	b: $b = \ln(B_{i_2}/B_{i_1})/\ln(D_{i_2}/D_{i_1})$	-0.592	-1.479	-1.446	-1.401	Equation 2
9	a: $a = B_{i_2}/(D_{i_2})^b$	2.66	2.66	2.52	2.27	Equation 3
10	Deaths per year in each ring = $(R/3.2)2\pi p_i a(D_{i_2}^{b+2} - D_{i_1}^{b+2})/(b+2)$	0.000240[b]	0.001365	0.001058	0.001580	Equation 1
11	Total deaths in all rings = D_x (deaths/yr)			0.004243[c]		ΣEquation 1

---

[a] Model types for each plant are shown in Table A-1, Reference 8, and in Table D-1 of this appendix.

[b] For this ring only, $D_{i_1} = 0.5$ in calculating p_i and deaths.

[c] This total appears in Table D-1 of this appendix.

The same calculations are made for ranges 0.1 to 1 km, 1 to 5 km, and 5 to 10 km, but there is one modification. In the calculation of population density ($p_{0.1-1}$) and number of deaths ($\bar{D}_{0.1-1}$), D_{i_1} is 0.5 km (not 0.1 km) because the population is assumed to reside in the area 0.5 to 1 km from the plant. In the calculation of b and a, $D_{i_1} = 0.1$ km.

The total annual leukemia deaths for the plant (D_x) are the sum of the deaths for each ring; i.e.:

$$\text{Deaths for Plant 4 } (\bar{D}_4) = \Sigma(\bar{D}_{0.1-1} + \bar{D}_{1-5} + \bar{D}_{5-10} + \bar{D}_{10-20})$$

$$\bar{D}_4 = 0.000240 + 0.001365 + 0.001058 + 0.001580$$

$$\bar{D}_4 = 0.004243 \text{ deaths/yr}$$

Deaths attributable to benzene emissions from any of the 143 plants may be calculated in the same manner.

D.4.4 Estimate of Leukemia Risk

The estimated leukemia deaths shown in Table D-1 are based on estimates of omnidirectional annual average benzene concentrations around benzene storage tanks. Because atmospheric dispersion patterns are not uniform, some population groups will receive above-average benzene exposures and will, therefore, incur a higher risk (or probability) of developing leukemia.

Maximum annual benzene concentrations were estimated as follows: For each model plant, the benzene storage tanks were assumed to be in a straight line parallel to the most prevalent wind direction, in order to maximize calculated annual average concentrations. The most prevalent wind direction in Lake Charles is south and north; thus, the storage tanks in each model plant were placed in a straight north-south line to maximize the combined effect of tank emissions on ambient air benzene concentrations.

Maximum annual risk is the estimated probability that a person who is constantly exposed to the highest maximum annual average benzene concentration in the ambient air around a particular source for 1 year will develop leukemia because of exposure to benzene emissions from that source. Maximum lifetime risk is estimated by multiplying the maximum annual risk by 70 years.

D.4.4.1 Example of Leukemia Risk Calculation. The maximum lifetime risk of leukemia was calculated for a person, who was assumed to reside at the point of highest maximum annual average benzene concentration outside the model plant with the greatest benzene emissions from benzene storage tanks. The maximum risk of leukemia associated with these emissions is calculated as follows:

First, the highest maximum annual average (MAA) benzene concentration associated with benzene storage tank emissions from any of the model plants is selected from Table 8 in Reference 9. This concentration, 16.8 $\mu g/m^3$, occurs 0.1 km from the plant boundary of the "large benzene producer" model plant. This model plant has a benzene production capacity of 224.6×10^6 liters/yr (Table 3-2).

Second, the benzene producer with the largest existing capacity is selected from Table 7-7. This producer, which is listed as Plant no. 4 in Table D-1, has a capacity of 700×10^6 liters/yr (185×10^6 gal/yr). The benzene concentration (16.8 $\mu g/m^3$) based on the model plant capacity of 224.6×10^6 liters/yr was scaled up proportionately to the existing plant capacity of 700×10^6 liter/yr; i.e.:

$$\text{Actual MAA benzene conc.} = (\text{model benzene conc.})\ \frac{(\text{actual plant capacity})}{(\text{model plant capacity})},$$

$$\text{Actual MAA benzene conc.} = (16.8)(700 \times 10^6/224.6 \times 10^6), \text{ or}$$

$$\text{Actual MAA benzene conc.} = 52.4\ \mu g/m^3.$$

This figure is converted from $\mu g/m^3$ to ppb by dividing by 3.2:

Maximum annual average benzene concentration = 52.4/3.2 = 16.4 ppb.

The result, 16.4 ppb, indicates that the person most exposed to benzene from any of the 143 plants, assuming he or she resides 0.1 km from the boundary of Model plant 4, receives an exposure of 16.4 ppb continuously, or for 1 person-year annually. By applying the risk factor[2] of 0.34×10^{-6} deaths per year per ppb-person year to this exposure, the annual risk can be calculated, viz:

$$\text{Maximum annual risk of leukemia} = (0.34 \times 10^{-6} \text{ deaths per year/ppb-person year}) \times (16.4 \text{ ppb-person years}), \text{ or}$$

$$\text{Maximum annual risk of leukemia} = 5.58 \times 10^{-6} .$$

Because lifetime risk is expressed as a probability to one person of dying of leukemia, the units have been deleted for convenience. Technically, the number represents deaths per year for one person. The lifetime risk of leukemia, assuming a 70-year lifespan, is simply 70 times the annual risk, or:

$$\text{Maximum lifetime risk of leukemia} = (5.58 \times 10^{-6})(70) = 3.9 \times 10^{-4}$$

The risk associated with the emissions from any specific plant or model plant may be calculated in the same manner.

D.4.5 Validity of Estimates

Several uncertainties exist in the estimated number of leukemia deaths and the maximum leukemia risk. Primary sources of uncertainty are listed below:

- Risk factor (R),
- Populations at risk,
- Estimated benzene concentrations around plants, and
- Benzene exposure calculations.

Uncertainties in the risk factor (R) are discussed in Section D.2.3, and uncertainties in populations "at risk" (P_i) are discussed in Section D.3. The other factors are discussed below.

D.4.5.1 Estimated Benzene Concentrations. The estimated benzene concentrations are derived from several factors which follow:

- Configuration of the model plant,
- Emission rates from the model plant, and
- Dispersion patterns of the emissions.

Uncertainties associated with these factors could not be quantified, but their qualitative effects on the estimated number of leukemia deaths are discussed below.

The configuration of the model plants assume from two to seven benzene storage tanks in a north-south line, with a center-to-center spacing of 183 meters. Current benzene emission rates from various type and size storage tanks were estimated and uniform emission rates assumed. Four emission models were used, and each model was matched with an actual plant. No corrections were made for differences between actual and model plant capacities (except in calculating maximum leukemia risk).

Several sources of uncertainty occur in the dispersion model. First, it is unlikely that any plant duplicates its corresponding model plant precisely, so uncertainties due both to differences in actual and model plant capacities and to assumed locations of tanks within plant boundaries may be expected. Second, the model used 1973-1976 weather data from Lake Charles (a near coastal city) to project dispersion patterns for all existing plants, and did not incorporate the effects of terrain. Thus, when applied to hilly, inland areas, the model may introduce inaccuracies. Third, the model assumes there is no loss of benzene from atmospheric reactions or ground level absorption. If such losses occur, the actual concentration of benzene will be less than the estimated values.

A final source of uncertainty is that the model measures benzene dispersion only to 20 km. If the linear risk model[2] is accurate, exposures at distances greater than 20 km, however small, may be important. If such exposures occur, the estimated number of deaths would be higher than estimated here.

It is estimated that benzene concentrations predicted by the dispersion model are accurate to within a factor of 2,[9] barring large inaccuracies in estimated benzene emission rates.

D.4.5.2 Benzene Exposure Calculations. Benzene exposure calculations assume that persons at specific locations are exposed 100 percent of the time to the benzene concentrations estimated to occur at each location. The assumption of continuous exposure to residents introduces some uncertainty, both in estimated number of leukemia deaths and in maximum leukemia risk. No numerical estimates of potential variation are available. Furthermore, the maximum lifetime risk assumes that a particular plant operates at full capacity for 70 years. There is necessarily a discrepancy between the methods used to measure distance from the plant for benzene concentrations and for populations. Benzene concentrations at the 0.1 km distance are measured from the plant boundary. This discrepancy introduces some imprecision (<2 percent) in the "ppb-person years" benzene exposure calculations used to estimate the number of leukemia deaths. The maximum lifetime risk estimate is not affected.

D.5 REFERENCES FOR APPENDIX D

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